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SOUND PRESSURE LEVELS MEASURED IN EAR-CANALS AND COUPLERS

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VERNON D. LARSON

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CHAPTER I

INTRODUCTION

An acoustic coupler is a key component in electroacoustic systems used to evaluate the performance characteristics of hearing aids. Couplers, having a volume of 2 cubic centimeters (cc) and a simple cylindrical shape, have been specified for this purpose by the American National Standards Institute (ANSI) (1,2). These simple devices are inexpensive in design and are intended to present approximately the same acoustic load to an earphone as does the average human ear.

The acoustic characteristics of the most commonly used 2-cc couplers do not exactly simulate the characteristics of the human ear. Differences between sound pressure levels (SPL) measured in these couplers and SPL recorded in real ear canals have been reported by many investigators (12,13,16,25,40,45,46). According to Beranek (6), Nichols, _et al._ in 1945 (41) showed that the sound pressure levels measured in a 2-cc coupler agreed with real ear measurements only up to 3.0 or 4.0

kilohertz (kHz). Similarly, studies by Van Eysbergen and Groen (54), McDonald and Studebaker (35), and Studebaker and Zachman (53) have shown that coupler and human ear-canal response is generally in accord only through 1.0 kHz. As frequency is increased above 1.0 kHz the sound pressure level in the coupler falls off progressively relative to that in the ear canal. Indeed, in 1961 the International Electrotechnical Commission recommended that the 2-cc coupler should be used only as a means for the exchange of physical performance data on hearing aids rather than for the prediction of performance of a hearing aid as it is worn by an individual (34).

In 1970, Zwislocki (60,61) developed a coupler which was intended to simulate more accurately the acoustic load presented by the average human ear. In 1972, Sachs and Burkhard (50) reported that ear canal data and Zwislocki coupler data were in good agreement at least to 5.0 kHz. Above 5.0 kHz sound pressure levels decreased in real ears relative to the coupler levels.

Several investigators have measured the sound pressure levels in the ear canal by placing a probe tube through the earmold material into the ear canal (9;27;35;49;50;53;57;58). Because placing the probe tube at the tympanic membrane is difficult under these circumstances, these investigators have terminated the probe tube in the same plane as the sound-inlet tube (or earmold bore), that is, at the tip of the earmold. Sachs and Burkhard (49) asserted that probe tube placement in relation to the sound inlet tube is critical when making measurements in a cylindrical tube such as a coupler. They reported that placement of a probe tube next to the sound-inlet tube and at the upper sidewall of a

2-cc coupler yielded differences of up to 20 dB in the frequency region above 2.0 kHz. For valid measurements in ear canals, Sachs and Burkhard suggested that the tip of the probe tube be extended 5 mm beyond the earmold tip.

The possible, but not yet demonstrated, discrepancy between SPL recorded at different probe-tube positions in human ear canals together with the absence of data concerning sound pressure levels recorded through an earmold at the eardrum prompted the current comparison of sound pressure levels, developed by hearing-aid receiver-earmold combinations, measured in real ears and in couplers. The frequencies above 1.0 kHz were of particular concern because other investigators have shown coupler versus ear canal differences in this frequency range (16, 25,35,50,53,58).

Specifically, the frequency response of the same receiver-earmold combinations was measured in the ear canals of normal-hearing subjects and in two acoustic couplers. The sound pressure levels observed at three positions in the ear canals were measured and compared with the sound pressure levels observed at the same positions in a 2-cc cavity and in the Zwislocki coupler. In addition, the sound pressure levels measured at the three locations in the ear canals were compared with each other; the sound pressure levels measured at the three locations in the 2-cc cavity were compared with each other; and the sound pressure levels measured at the three locations in the Zwislocki coupler were compared with each other.

CHAPTER II

REVIEW OF THE LITERATURE

Introduction

Devices used to simulate the acoustic properties of the human ear for purposes of testing earphones have been used for many years (3, 6,11,15,18,30,36). Inglis, Grey, and Jenkins (22) developed one such device, called an artificial ear, in 1932 (6). This artificial ear had an acoustic network incorporated within its design, and it presented to an earphone under test an acoustic impedance very similar to that which would be presented by the average human ear (6). Since 1932, numerous other artificial ears which incorporated acoustic networks within their designs have been described (3,15,23,37,60,61).

Because these artificial ears were difficult to reproduce by different laboratories (6,18,45), it became accepted practice to use artificial ears which were simple in construction and were easily standardized (6). Such a device is referred to as a coupler (6). For the last thirty-five years, the calibration of hearing-aid receivers has been carried out using simple cyclindrical couplers having a volume of approximately 2 cc (18).

The Use of 2-cc Couplers in Hearing Aid Receiver Testing

Schier (51) alluded to the use of a coupler by the Sonotone Corporation in hearing-aid receiver testing as early as 1938. Between 1942 and 1946 Romanow (45), Sabine (46), LeBel (29), Nichols (40), Nichols (41) and Wiener and Filler (58) reported the use of couplers having a 2-cc cavity. According to Romanow, this cavity was chosen to represent the average volume left in the ear after the insertion of an earmold. Each of these couplers had a sound-inlet channel to the 2-cc cavity of 0.710 inches in length and 0.120 inches in diameter. The sound-inlet channel dimensions presumably represented the average bore in commercially-available earmolds. The SPL in the cavity was measured by a condenser microphone, the diaphragm of which served as the bottom of the cavity.

During and after World War II, a 2-cc coupler with these dimensions was known as the Joint Radio Board (JRB) coupler. The JRB coupler became the generally accepted instrument for making insert earphone (e.g. hearing-aid receiver) measurements (18). Glaser and Morrical described another 2-cc coupler, the Massa M112 (18). It differed from the JRB coupler primarily in that the microphone was inserted into the side rather than into the bottom of the coupler. In an acoustic comparison of these two couplers, they determined that the sound pressure levels developed in the JRB coupler were considerably less than the SPL developed in the Massa coupler in the frequency region above 1.5 kHz. Since both couplers had hard walls and the same volume, Glaser and Mornical expected the response to be purely determined by compliance. Therefore, the acoustic response should have been identical. The difference was attributed to a "dissipative element" associated with the JRB coupler which was not associated with the M112 coupler.

In 1945, the Engineers' Committee of the American Hearing Aid Association promulgated a tentative code for hearing-aid measurements (6,28). The committee advocated the use of the 2-cc coupler which, in slightly modified form, was later adopted by the American Standards Association and designated as the Type 2. In 1949, the American Standards Association specified the design of couplers to be used in hearing-aid receiver testing (1). One type of coupler, called the Type 1, was a simple 2-cc cavity. This coupler was intended for use in the calibration of a hearing aid receiver which was attached to an earmold. A second coupler, the Type 2, was designed to accomodate the direct coupling of a hearing-aid receiver.

The basic features of the Type 2 coupler are shown in Figure 1. A 0.120 inches diameter by 0.710 inches length sound-inlet bore was terminated in a cavity which had a volume of approximately 2 cc. The actual volume of the cavity was adjusted so that the equivalent volume of the condenser microphone located at the cavity's bottom together with the actual volume of the cavity equalled 2 cc. A capillary was included in the cavity to provide equalization of static pressure in the coupler. This leak did not affect the frequency response appreciably within the frequency range of interest in hearing-aid measurements (11).

The dimensions of the JRB coupler bore were the same as that of the Type 2. However, the couplers differed in that the equivalent volume of the JRB coupler's microphone was not considered to be a part of the total volume of 2 cc. In addition, the pressure-equalization capillary was not present in the JRB coupler.

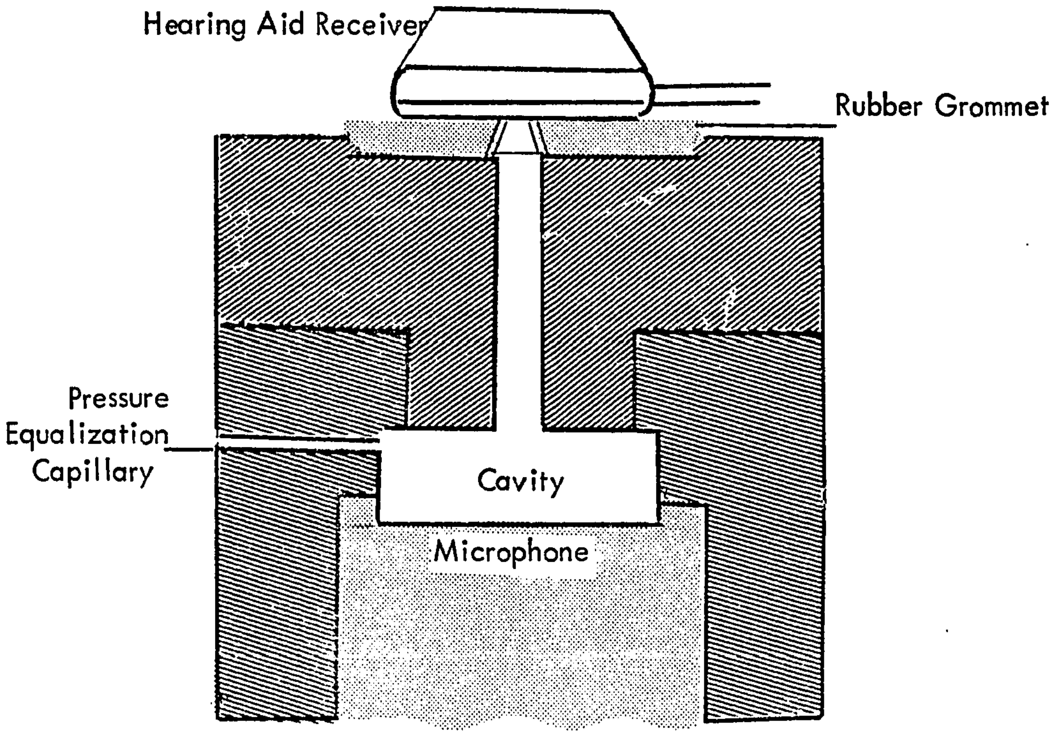


Figure 1. The American Standards Association Type 2 Coupler. This illustration is not drawn to scale.

In 1961, the American Standards Association specified designs for three couplers to be used for hearing-aid receiver testing (2). The HA-1 coupler was very similar to the earlier Type 1. The HA-2 coupler was nearly identical to the Type 2. The HA-3 coupler was designed to accomodate a length of tubing which connects to hearing-aid receivers of the internal type such as are used with ear-level hearing aids.

While the cavity specifications were the same in the 1961 document as they were in the 1949 standard, changes in the bore length and bore diameter were made in the HA-2 coupler. The bore diameter was reduced to 0.118 inches (3mm) and the bore length was reduced to 0.709 inches (18mm). The reason for these changes were not explained in the standard, but it is possible that the changes were made simply to achieve a whole-number metric expression of the coupler's dimensions.

SPL Measured in 2-cc Couplers and in Human Ears

Although 2-cc couplers have been used for more than three decades, even early investigators were aware that coupler SPL did not agree with SPL developed in the human ear canal. According to McMartin (36), differences between the acoustic responses of ears and couplers were known at least 25 years ago.

In 1941, Romanow (45) reported data which suggested a difference between SPL developed in human ears and the 2-cc coupler. He asked listeners to balance the loudness of signals delivered by a loudspeaker to the loudness of signals delivered by a hearing-aid receiver through an earmold which was situated in the ear canal. The hearing-aid receiver was then placed on a 2-cc coupler, and, with the same voltage driving the receiver, the coupler SPLs were noted. The differences Romanow noted were based on SPL measured in an undisturbed sound-field and the SPL developed in the coupler. His measurements showed that sound pressures developed in the coupler were less than those developed in the real ear as inferred from the loudness balance procedures. Low-frequency differences were explained on the basis of leakage around the earmold. Citing Sivian and White's (52) minimum-audible pressure versus minimum-audible field differences, Romanow attributed discrepancies of up to 10 dB in the region above 1.5 kHz to the diffraction of sound about the head and to the resonance characteristics of the ear canal.

In 1944, Sabine (46) stated that the SPL in ear canals differed from those developed in a coupler. He attributed differences to the resonance of the open cavity of the ear.

In 1944, LeBel (29) substantiated coupler and sound-field differences observed by Romanow. LeBel averaged the sound-field data and eardrum-pressure data of Fletcher and Munson (17) and of Sivian and White (52) in an attempt to isolate the effects of the head and ear canal. In considering coupler versus sound-field differences in light of the Fletcher-Munson and Sivian and White data, LeBel concluded that coupler and sound-field differences could be attributed only partially to the pressure vs. field response of the ear. The remaining fraction, he asserted, was due to differences between the acoustic impedance of the coupler and the human ear.

Beranek (6) has reported that Nichols _et al_. (41) showed in 1945 that the average sound pressure level developed in ear canals was up to 10 dB greater than those developed in a 2-cc coupler.

The difference varied, however, with the type of receiver (magnetic and and crystal) tested. Apparently these ear canal measurements were made with a probe tube extending through an earmold and terminating at the tip of the earmold. It is unclear from Beranek's account whether coupler measurements were made with a probe tube in the same position in the coupler as in the ear canal or whether they were taken from the microphone located in the coupler bottom.

Wiener and Filler (58) also made probe-tube measurements through an earmold which was seated in ear canals and compared them to the levels developed in a 2-cc coupler. For two receivers, the agreement between ear canal and coupler pressures was exceptionally good. As in the former instance, it is not known whether coupler levels were measured by probe-tube techniques or by means of a coupler microphone, but the lack of discussion fosters the inference that the measurements were taken from the coupler microphone.

Nichols (40) speculated that differences between levels developed in the human ear canal and couplers appear because the soft walls of the ear canal provide more damping of the peaks than do the hard walls of the coupler.

Morton and Jones (38) studied the acoustic impedance of couplers and of human ears. They found that the mean reactance at the tip of an earmold in the human ear canal was negative in the low frequencies, but it became positive above 2.5 kHz. The 2-cc coupler, on the other hand, exhibited a negative reactance at all frequencies. In addition, the resistance of the real ears at the tip of the ear insert was 100 acoustic ohms while the resistance of the coupler was zero.

Morton (37) compared the 1.5-cc National Physical Laboratory (England) coupler and the HA-2 coupler with a coupler which he developed together with Jones (38). The latter coupler had a cavity volume of 0.86 cc, a bore length of 1.85 cm and a diameter of 0.249 cm. The coupler designed by Morton and Jones more closely approximated frequency response tracings recorded in human ear canals.

In 1957, Ewertsen, Ipsen and Nielsen (16) measured the frequency response in the ear canals of six subjects and compared them to HA-2 coupler sound pressure levels. A probe tube was inserted into the ear canals and into the coupler through the earmold so that its end terminated flush with the earmold tip. (The probe tube was first corrected for its attenuation using measurements made in a coupler.) The ear canal and coupler differences reported were based on the relationship between the corrected probe measurements and measurements made with the microphone placed in the coupler bottom. Their data showed that levels developed in the coupler were approximately 5 dB less through 1.5 kHz. Above 2.0 kHz, coupler levels were as much as 12 dB less than those developed in the ear canals.

In 1956, Jonkhoff (25), in an unpublished thesis, used a loudness balance technique for an estimate of SPL in human ear canals and found that beyond 3.0 kHz, the level in a 2-cc coupler fell off sharply relative to that in the human ear canal.

In 1959, van Eysbergen and Groen (54) reported a study in which monaural pure-tone thresholds were established in sound field. These thresholds were "...converted into sound pressure units by measuring the output of the loudspeaker with the human ear replaced by a condenser microphone." They also established thresholds with the sound delivered to the ear by an insert earphone driven by an oscillator. Thresholds were established using two types of earpieces: one with a narrow tip and one with a wide tip. After thresholds were established, SPL in a 2-cc coupler were determined. Both low- and high-frequency differences were observed between coupler and and field pressures. Low-frequency differences were attributed to leaks between the ear insert (earmold) and the walls of the meatus and to insert bore-size differences. Differences of 20 dB were present above 3.0 kHz; these were attributed to the "...design of the couplers".

In 1970, Studebaker and Zachman (53) as a part of a larger study reported a comparison between real ear and 2-cc cavity data. In their research they used earmolds having bores acoustically equivalent to the bore of an HA-2 coupler. They used a probe-tube technique to measure SPL at the tip of the earmold in one ear canal of each of four subjects. The probe-tube frequency response had been corrected previously by measurements made in a closed coupler; however, Studebaker and Zachman ascertained an interaction between the apparent calibration of the probe tube and the acoustic environment in which it was placed. Acknowledging this interaction, they observed that coupler sound pressure levels were up to 7 dB greater than levels measured in the ear canals in the 0.4 kHz region. The levels were in good agreement in the 0.6 to 1.0 kHz region. In the 1.5 to 5 kHz region, levels in the coupler fell below those in the real ear canals by 5 to 7 dB.

McDonald and Studebaker (35) also compared sound pressure levels developed in ear canals and in couplers. They cited the interaction mentioned earlier by Studebaker and Zachman and suggest that the accuracy of their probe-tube calibration was not precisely known. Their ear canal data in comparison with their coupler findings showed only slight differences in the frequency region below 0.8 kHz. Above that frequency, the level in the coupler fell 7-8 dB below that in the ear canals as frequency was increased.

Another recent comparison of sound levels in ear canals and couplers was made by Sachs and Burkhard (50). The same input tubing was used to deliver sound to ear canals (through earmolds) and to a 2-cc coupler cavity. A probe tube was placed through an earmold, and the orifice of the tube was terminated 5 mm beyond the earmold tip. Sound pressures in the coupler were measured using the probe tube, also inserted 5 mm beyond the opening of the sound inlet bore. Coupler sound pressure levels were found to be 3 to 5 dB less than those in the ear canals at frequencies below 1.0 kHz. Above 1.5 kHz, coupler sound pressure levels fell off progressively as frequency was increased. The difference reached a maximum of 10.5 dB at 4.5 kHz.

In an effort to compare sound pressure levels measured at 5 mm beyond the earmold tip with what they believed would have been measured at the tympanic membrane, Sachs and Burkhard utilized sound pressure transformation data published by Zwislocki (60,61) representing the differences between the levels measured at the eardrum and at a point 1 cm from the ear canal entrance. With this transformation, a comparison of the calculated sound pressures at the eardrum with those developed in a 2-cc coupler showed that the levels at the eardrum would exceed those at the analogous position in couplers to an even greater extent than indicated at other measurement positions. At 4.5 kHz and above, for example, the difference increased up to 15 dB.

Zwislocki's Coupler

Noting that it is "almost incredible" that standard couplers have survived thirty years of use, Zwislocki (60,61) developed an "ear-like" coupler which may be adapted for use in testing hearing-aid receivers as well as earphones.

Inspired by the suggestions of Working Group 48 of the Committee on Hearing, Bioacoustics and Biomechanics of the National Research Council, National Academy of Sciences, the ear-like coupler was developed following extensive research mainly involving acoustic impedance measurements at the eardrum, sound pressure measurements in the outer ear, and measurements of the dimensions of the ear. Figure 2 is an illustration of the device as used when testing hearing-aid receivers.

The device is mounted on a Bruel and Kjaer one-half inch condenser microphone. A sound-inlet bore is not part of the device. The bolt-like structures protruding from the coupler are the acoustic networks that are used to simulate the acoustic impedance of the human eardrum. The coupler also includes a cavity analogous to that existing between the tip of an ear insert and the eardrum.

Sound Pressure Levels Measured in the Ear-Like Coupler and in Human Ear Canals

In his evaluation of the ear-like coupler for hearing-aid receiver testing, Zwislocki (60,61) made probe-tube measurements at the eardrum in human ear canals and at a point 0.9 cm from the entrance of the canal. The latter position corresponds approximately to the location

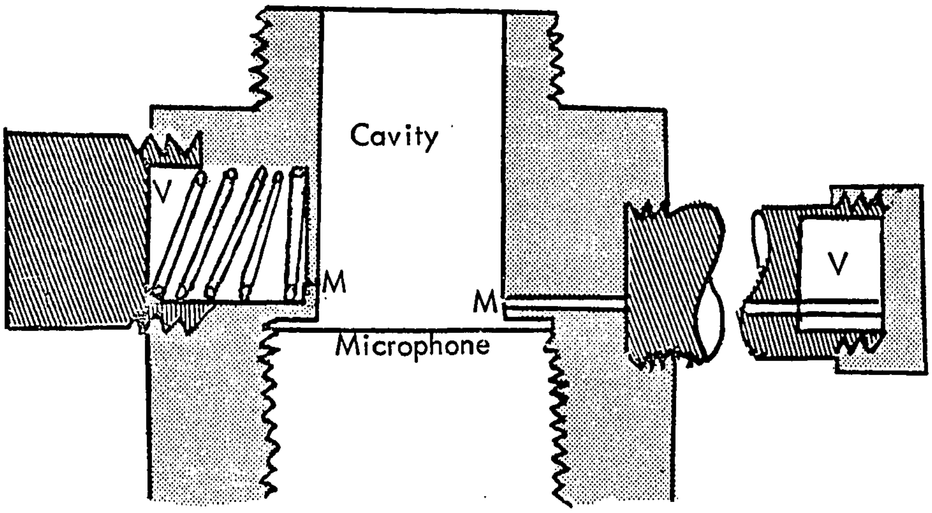


Figure 2. Longitudinal section of the portion of the Zwislocki coupler which is used in the testing of hearing-aid receivers. The letter V indicates an air volume while the letter M indicate openings into two resonators. (This illustration is not drawn to scale).

of the tip of commonly used earmolds as worn in the ear canal. Sound pressure ratios at frequencies in the range of 0.2 to 10 kHz were determined from the measurements made at these two positions. Corresponding sound pressure ratios based on coupler measurements were also determined. These measurements were made "...in the same way as in the ear". A comparison of these ratios showed that coupler and ear canal values were within 1 dB at all frequencies except at 7 kHz and 10 kHz. At 7 kHz, the coupler value was greater by 3.5 dB while at 10 kHz, the coupler value was smaller by 3.0 dB.

Sachs and Burkhard (50) also compared sound pressure levels in human ear canals with those measured in a Zwislocki coupler. In both instances, the probe tube was extended 5 mm beyond the earmold tip to avoid effects of proximity of the sound inlet tube to the probe tube. As in their comparison of ear-canal and 2-cc coupler SPL, Sachs and Burkhard calculated the levels at the eardrum by adding Zwislocki's sound pressure transformation data to their observed data. Below 0.8 kHz, pressure in the coupler was essentially identical to pressure in the ear canals of eleven subjects. They reported that from 0.8 kHz to 7.5 kHz the mean pressure in real ears and in the Zwislocki coupler differed by no more than 3 dB. An inspection of their data reveals that the two are generally not different by more than 1.5 dB. This comparison, of course, assumes that the SPLs existant at the eardrum were accurately predicted by the calculations which Sachs and Burkhard employed.

Summary

There is substantial evidence that significant differences exist between the SPL measured in human ear canals and in 2-cc couplers, particularly in the higher frequency range. Early work comparing the frequency response in ear canals with that measured in couplers did not fully account for diffraction effects of the head and the resonance characteristics of the ear canal because probe-tube measurements were not made in the ear canals. The data obtained by later workers may have been confounded, at least at the higher frequencies, by the practice of making probe-tube measurements through an earmold with the probe-tube tip terminated at a point adjacent to the outlet of the sound-inlet tube.

In his evaluation of the ear-like coupler, Zwislocki did not make measurements in ear canals with earmolds in place or analogous measures in the couplers. Sachs and Burkhard did not compare levels in the Zwislocki coupler with sound pressure levels actually measured at the tympanic membrane.

There appeared to be a need for a study describing the relationship between sound pressure levels developed in analogous positions in a 2-cc cavity, the ear-like coupler and in human ear canals (particularly at the eardrum) when in all instances the sound source was a hearing-aid receiver-earmold combination. This investigation was designed to collect data which would allow these comparisons to be made, with particular emphasis placed on the frequency range above 1.0 kHz.

CHAPTER III

INSTRUMENTATION AND PROCEDURE

Introduction

The purpose of this investigation was to compare the acoustic characteristics of a hearing-aid receiver (attached to earmolds) placed on couplers with the performance of that same receiver (attached to earmolds) seated in the human ear canal. The acoustic output for frequencies in the range from 0.8 kHz to 6.4 kHz was observed at three locations in the ear canals of eight normal-hearing listeners. One set of measurements was made with the probe-tube terminated at the tip of the earmolds (designated the 0-mm position). Another set of measurements was made with the probe-tube tip at a point 5 mm beyond the earmold tip (designated the 5-mm position). The third set of measurements involved alternate binaural loudness balance judgements together with probe-tube measurements of the sound pressure level at a position 1 mm from the opposite tympanic membrane. This technique was utilized as a means of deriving the sound pressure level at the eardrum of an ear occluded by an earmold.

The sound pressure levels recorded at each of the probe-tube positions in the ear canals were compared with the sound pressure levels developed by a receiver-earmold combination at the three analogous positions in a 2-cc cavity (comparable to the HA-1 coupler) and in a Zwislocki coupler. That is, probe-tube measurements were made at the 0-mm and the 5-mm positions, as well as at a position 1 mm from the coupler bottoms.

Subjects

Eight male adult subjects between the ages of 22 and 30 years were used in this study. Each subject had hearing sensitivity, measured by air-conduction for each ear, no poorer than 10 dB re the ANSI (1969) standard at the frequencies 0.25, 0.5, 1.0, 2.0, 4.0 and 8.0 kHz. Bone-conduction thresholds were within 10 dB of the air-conduction thresholds for the same frequencies. In addition, air-conduction thresholds were established at the frequencies 0.8, 1.2, 2.4, 2.8, 3.2, 3.6, 4.0, 4.4, 4.8, 5.2, 5.6, 6.0, and 6.4 kHz using a Bekesy audiometer (E-800). The threshold at a given frequency for one ear of a particular subject generally did not differ from that of the opposite ear by more than 5 dB. With the exception of one frequency for each of two subjects, the thresholds for one ear were never different from those of the opposite ear by more than 10 dB. Each subject was free from external and middle ear pathology as determined by an otological evaluation and by testing with an electro-acoustic impedance bridge (Madsen ZO 70). Each tympanogram was classifiable as a Type A and, in addition, the compliance value for each ear fell well within the range considered to be normal (24,44).

Test Environment

All measurements were made in a sound-treated room located in the Department of Communication Disorders, the University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma. Ambient-noise levels in this environment were measured using a General Radio sound-level meter (model 1552-P) used in conjunction with a General Radio octave-band analyzer (model 1558-AP). In the octave bands between 0.125 kHz and 8.0 kHz, the noise levels were observed to be 30 dB less than the levels of the signals used in the loudness balance portion of this investigation. During the ear canal measurements and during the coupler measurements, a wave analyzer (Hewlett-Packard, model 302A) was used to extract low-level signals from noise. The noise levels through the wave analyzer relative to the observed signal levels were observed throughout the investigation and were never greater than -15.0 dB.

Instrumentation

Signal Generation and Control Instrumentation

Figure 2 is a block diagram of the equipment employed to generate and control the pure-tone signals which were used in all phases of this study.

The output of a beat-frequency oscillator (General Radio, model 1304-B) was divided. One output (channel 1) of the dividing network was routed to an electronic switch (Grason-Stadler, model 829E). The output of this switch was directed to a one-decibel step attenuator (Hewlett-Packard, model 350 AR) which was operated by the examiner. The output of the examiner's attenuator was directed through an isolation pad to an amplifier (McIntosh, type A-116-B). A 600-ohm resistor was paralleled across the output of the pad in order to provide the attenuator with the proper resistive load. The output of the amplifier could be directed to a recording attenuator (Grason-Stadler, model E3262A) or to a Bruel and Kjaer (B & K) hearing-aid receiver (type HT0003). The output of the

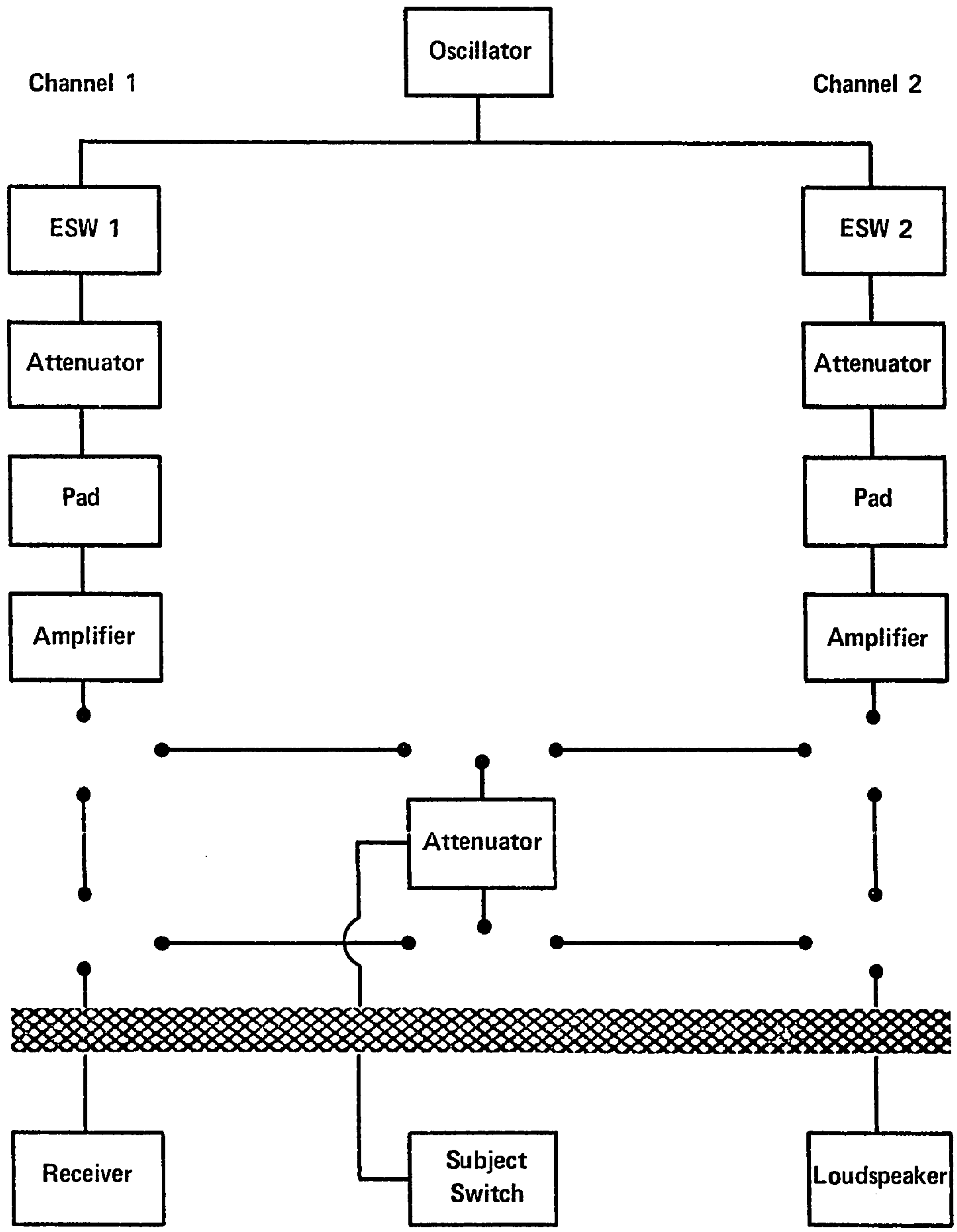


Figure 3. Block diagram of signal generation and control equipment.

amplifier was terminated with an 8-ohm resistor (100 watt) in order to assure a proper load. The recording attenuator was operated by the subject by means of a switch. The attenuation rate was set at 1.0 dB per second and the chart speed of the attenuator was 45 inches per hour. The air-conduction hearing-aid receiver whose electrical input impedance was measured as being 980 ohms at 1.0 kHz, terminated channel 1. The amplifier provided a very low source impedance. This constant voltage source arrangement (low source impedance and high load impedance) is such that the source voltage is least affected by changes in acoustic loading on the receiver (34).

The other output from the divider (channel 2) was directed to a second electronic switch (Grason-Stadler, model 829E). The output from the switch was directed to a one-decibel step attenuator (Hewlett-Packard, model 350AR), through an isolation pad and to an amplifier (McIntosh, type A-116-B) in the same manner as in channel 1. The output of the amplifier could be directed to the recording attenuator or to an 8-ohm loudspeaker (Acoustic Research, model 4X).

A voltmeter (Ballantine, model 300) was connected across the terminals of the hearing-aid receiver to monitor the voltage changes effected by the subject in the loudness balance experiment. A digital counter (Darcy, type 361A-R) was inserted into the circuit in parallel with the oscillator to monitor the frequency of the test signals. Periodically, an oscilloscope (Tektronix, type 2A63) was used to monitor the waveform of the test signals.

The test signals were alternately turned on and off by the two electronic switches. These switches were triggered externally with the timing network shown in Figure 3. This network consisted of three waveform generators (Tektronix, type 162) and five pulse generators (Tektronix, type 161). Waveform generator (WFG) operated in recurrent mode, triggered pulse generators (PG) 1 and 2. Pulse generator 1, set for a 500 msec delay, turned on electronic switch (ESW) 1. Then WFG 2 and PG 3 governed a 500 msec delay. At the end of this interval, PG 3 turned off ESW 1. Pulse generator 2 triggered WFG 3 which in turn activated PG 4. Pulse Generator 4 turned on ESW 2 500 msec after ESW 1 was turned off. WFG 3 also activated PG 5 which turned off ESW 2 after a 500 msec interval.

Earmolds

Impressions were made of the right and left ears of the subjects using commercially available impression material (Audalin, U.S.Patent no. 3,588,500), following the general procedure outlined by Watson and Tolan (56) except that a syringe was used to insert the impression material (8,39). All subjects were examined by an otologist. The ear canals were also further inspected for debris by the investigator at the time the impressions were made. A cotton block was placed in the bony portion of the ear canal. Powder and liquid portions of the earmold material were carefully measured in order to reduce the possibility of shrinkage in the earmold impressions (20). The impressions were taken immediately to a local earmold laboratory.

The earmolds were fabricated from the earmold impressions into permanent form by the earmold laboratory. The finished earmolds differed from commercially available standard earmolds only in that the snap ring and associated snap ring recess were eliminated. The snap ring configuration was eliminated in order to reduce the intermold variability

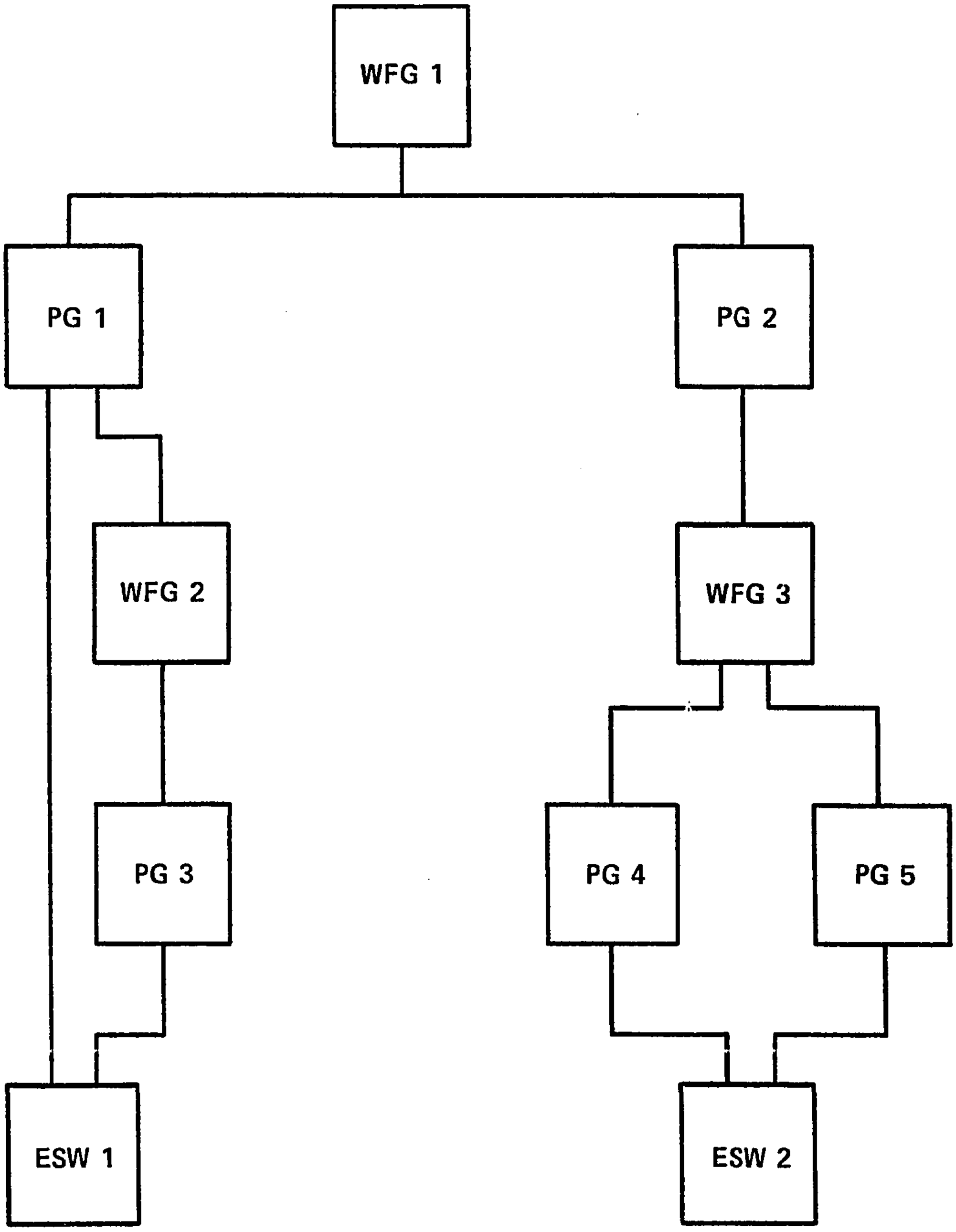


Figure 4. Block diagram of signal timing equipment.

attributable to variations in the sound input channel (34). All earmolds were drilled to accomodate tygon (42) sound-input tubing with an inside diameter of 2 mm (0.076"). This tubing is usually referred to as size 13 tubing by the hearing aid industry (8). The tygon sound-inlet tubing had a length of 25 mm for each earmold and terminated with a plastic adaptor which accomodated the hearing aid receiver nubbin.

A hole for the probe tubing was drilled in each earmold approximately parallel to the bore which housed the sound-inlet tube. The orifice of this tube terminated adjacent to and on a plane with that of the bore aperture. The distance between the center of the sound-inlet tube and the center of the probe tube was 3 mm.

The anterior - posterior (AP) and superior - inferior (SI) dimensions of the 16 finished earmolds were measured in order to provide an estimate of the size of the ear canals of the subjects used in this investigation. Measured at approximately 2 mm from the earmold tip, the mean AP distance was 7.3 mm with a standard deviation of 1.10. The mean SI distance was 10.1 mm with a standard deviation of 0.87. These estimates are very similar to the measurements made by Zachman (59). For four earmolds, he reported a mean AP dimension of 7.0 mm (S.D. of 0.71) and a mean SI dimension of 11.3 (S.D. of 0.90). In similar measurements taken on 100 randomly selected earmolds from the stock of an earmold manufacturer, Zachman (59) found a mean AP dimension of 7.8 mm with a standard deviation of 0.81 mm while the mean SI dimension of the 100 earmolds was 12.1 mm with a standard deviation of 1.3 mm.

Probe Tubing

Preliminary experimentation showed that the use of commercially available tygon tubing for probe tubes did not provide repeatable measurements. This variability may have been due to slight narrowing of the tubing at bends which may have altered the acoustic response. Alternatively, the probe tubes which were used in this investigation were formed from a malleable, heat-shrinkable polyolefin tubing. A stainless steel tube with an outside diameter of 1 mm (B & K probe kit, model UA 0030) was inserted inside a length of heat-shrinkable tubing. Heat was then applied. The result was a fairly rigid but flexible tubing with an outside diameter of about 2 mm and an inside diameter of 1 mm. Three probe tubes of 55 mm in length were formed in this way. Repeated frequency-response measurements made in a 2-cc coupler (B & K, type DB 0138) showed that the variability from one measurement to the next (at a given frequency) was no more than 0.5 dB for the frequencies between 0.8 and 6.4 kHz. In addition, the frequency response of each tube varied no more than 1.0 dB from the other two throughout the same frequency range. Two of the three tubes were utilized in the coupler and in the ear canal measurements. The response of the tubes was checked four times during the course of the experiment. Deviations greater than 1.5 dB at any frequency were not observed at any time.

Couplers and Associated Instrumentation

The HA-2 coupler, often referred to as the standard 2-cc coupler, includes a metal cylinder with a 3 x 18 mm hole bored through it. The bore terminates with the 2-cc cavity. (The actual size of the cavity is adjusted to compensate for the equivalent volume of the microphone diaphragm so as to give a total volume of 2 cc). The diaphragm of a one-inch condenser microphone is the bottom of the cavity. For this investigation, a modified coupler was manufactured by the Instruments Shop, Physics Department, University of Oklahoma, Norman, Oklahoma. The modified coupler, comparable to the HA-1 coupler, on which an earmold is mounted is illustrated in Figure 5. This coupler has the same volume as the HA-2 coupler, but the cylinder containing the 3 x 18 mm bore has been eliminated.

A Zwislocki coupler was also machined by the University of Oklahoma Instrument Shop. Figure 2 (page 15) illustrates that portion of the device used in testing hearing-aid receivers. Following the manufacture of this coupler, it was sent to its designer, J. J. Zwislocki, for evaluation prior to its use in these experiments. The Zwislocki coupler was tested by B. Klock of Zwislocki's laboratory and was said to meet design specifications in all respects (26).

The receiver-earmold combinations were placed on the 2-cc cavity as shown in Figure 5. They were placed on the Zwislocki coupler in the same way. A one inch microphone (B & K type 4132) and a cathode follower (B & K type 2615) were used to measure SPL in the modified coupler. A one-half inch microphone (B & K type 4134) and a cathode follower (B & K type 2613) were used to measure SPL in the Zwislocki coupler. Figure 6 shows the instrumentation used in the coupler SPL measurements. The appropriate microphone was placed in the bottom of each coupler. Cathode followers were connected to microphone amplifiers. The output of each microphone amplifier (B & K type 2603) was directed to a wave analyzer

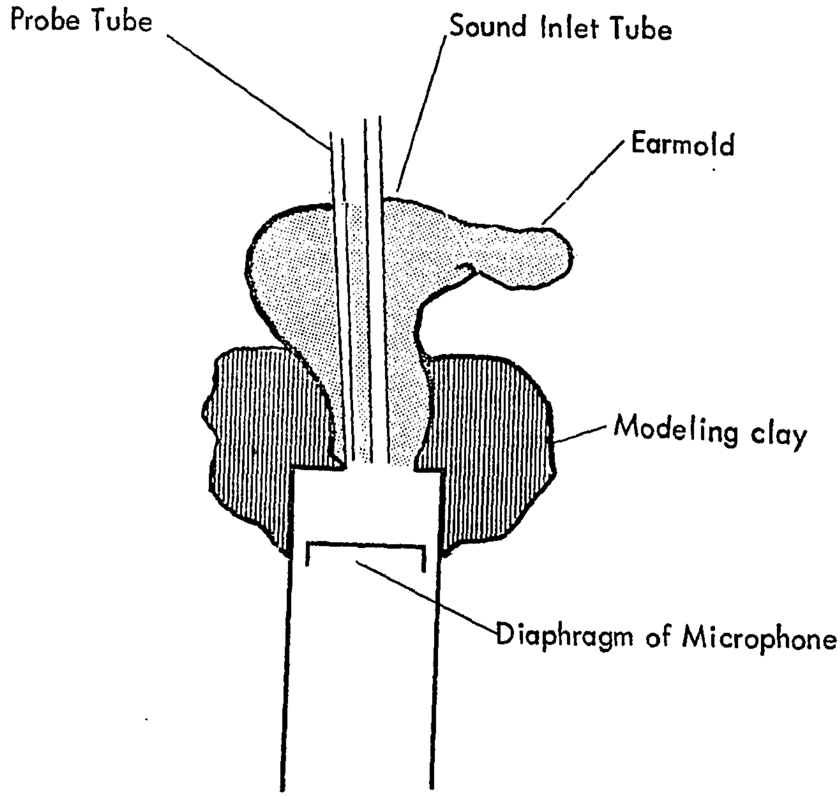


Figure 5. Earmold mounted on the 2-cc cavity. (This illustration is not drawn to scale.)

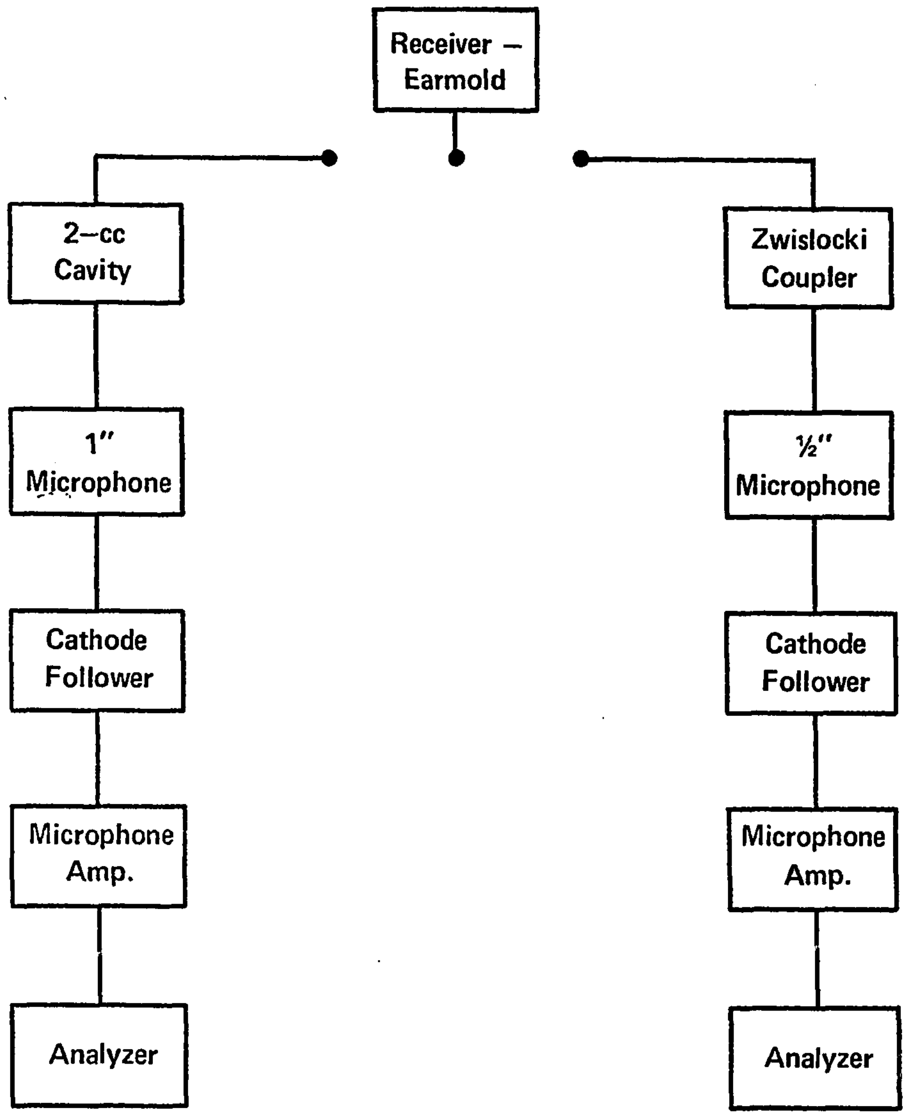


Figure 6. Block diagram of instrumentation used in the coupler measurements.

(Hewlett-Packard, model 302). The wave analyzer was operated in the relative mode rather than the absolute mode. For each series of measurements in which the analyzer was used, a sound pressure level reference was set at 0 dB on the wave analyzer scale. Sound pressures developed at the microphone were then read from the wave analyzer's meter and recorded relative to the prescribed sound pressure level reference. For sound pressure level measurements through earmolds at the three measurement positions, a probe tube was inserted into the 2-mm probe-tube adapter of the Bruel and Kjaer (B & K) assembly which was used with the one-half inch microphone and cathode follower. Sound pressure levels were observed using the microphone amplifier, the output of which was directed to the wave analyzer. The wave analyzer was used for these measurements in the manner previously described.

Instruments and Apparatus for Sound Pressure Level Measurements in the Ear Canals

For sound pressure level measurements through earmolds at the two positions in the ear canals and at the tympanic membrane of the unoccluded ear, a probe tube was inserted into the 2-mm probe-tube adapter of the B & K assembly, which was used with the one-half inch microphone. Sound pressure levels were measured with a microphone amplifier. The microphone amplifier's output was directed to the wave analyzer. The wave analyzer was used for these measurements in the manner previously described.

For the ear canal measurements, an apparatus was constructed to secure firmly the subject's head. The basic support structure was a dental chair, modified so that the head rest butted against the side of the subject's head. An adjustable rubber headband was fastened to the head rest in order to fix the subject's head in position.

Figure 7 shows a portion of this apparatus. A 4.45 cm (1.75 inches), L - shaped section of steel was bolted to a head rest and was extended over the subject's head. This section provided a stable mount for a portion of a Moore and Wright micromanipulator which allowed for both horizontal and vertical adjustment of the probe tube holding apparatus (for measurements in the unoccluded ear canal). A 0.97 cm (3/8 inches) diameter section of metal rod was attached to the manipulator section. A clamp, located at the end of the metal rod, was used to hold the cathode follower and its associated conical adapter which houses the probe tube. An adjustable clamp assembly was attached to the head-rest side of the apparatus in order to hold the cathode follower associated with probe-tube measurements through the earmold.

Procedure

Preliminary Measurements

For each coupler and each probe tube position in the couplers, sound pressure level measurements were made from the coupler microphone once with the probe tube aperture open and once with the probe tube aperture occluded with modeling clay. This was done at the frequencies 0.8, 1.2, 2.0, 2.8, 3.6, 4.4, 5.6, 6.0 and 6.4 kHz in order to ascertain the effect of the presence of the probe tube at the three positions in each coupler's cavity.

The transmission of sound through the walls of the probe was also checked. This was done by measuring the sound levels inside a

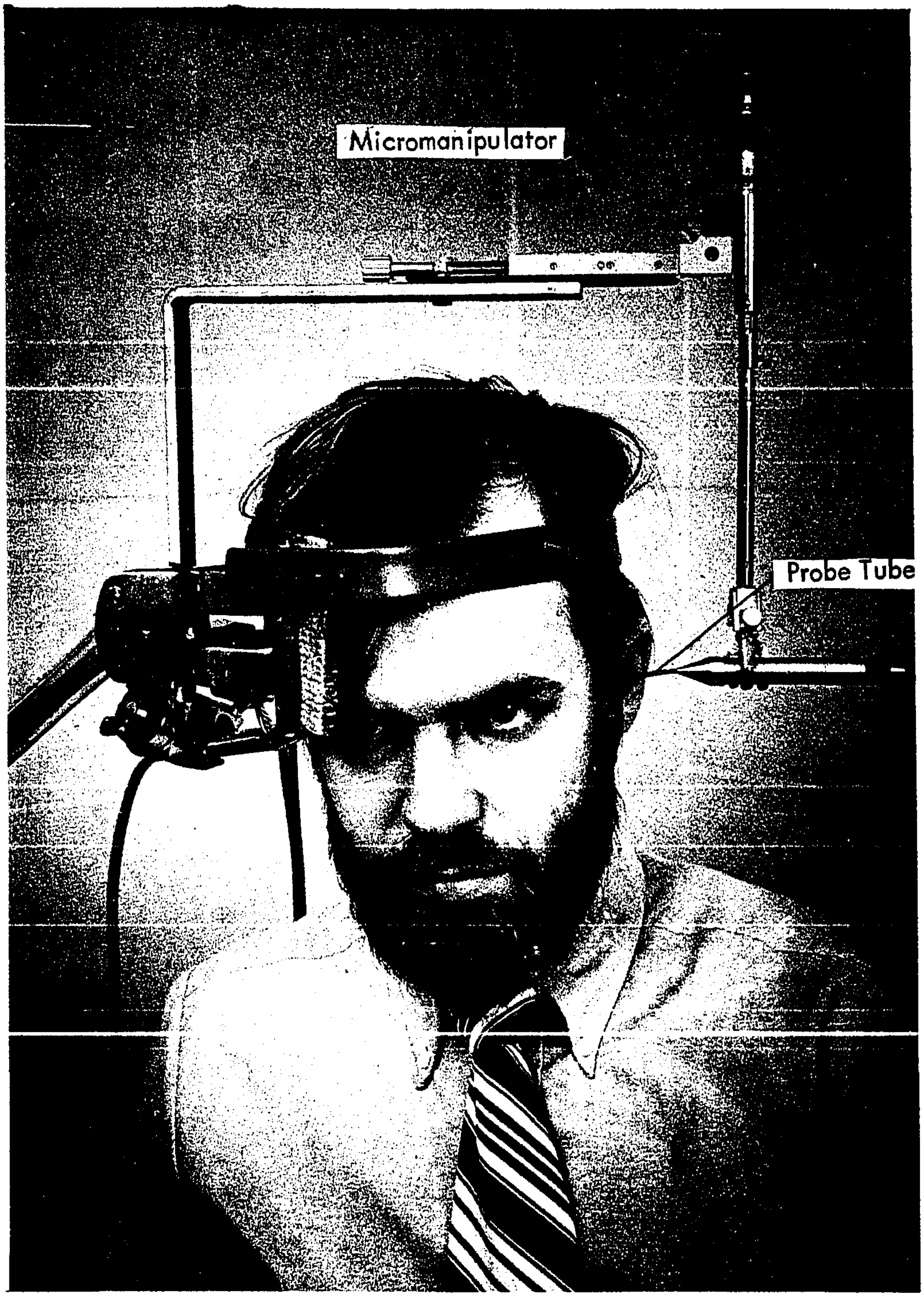


Figure 7. Photograph of head-rest support apparatus and probe-tube adjustment apparatus.

coupler cavity (B and K, type 0148) first with the probe-tube aperture open and then with the aperture occluded. The difference between the two sets of measurements represented the transmission of sound through the walls of the probe tube.

Sound Pressure Level Measurements in the Couplers

Measurements were made from the probe-tube microphone with the probe-tube tip placed at each of the three positions (0 and 5 mm from the earmold tip and 1 mm from the coupler bottom) in each coupler. Measurements were also made from the coupler microphone without the probe tube present and the probe-tube hole blocked with modeling clay.

Sixteen earmolds were used in this portion of the study. The sound inlet tubing of each earmold was connected to the hearing-aid receiver by means of a plastic adaptor. Each earmold was mounted on the 2-cc cavity and on the Zwislocki coupler. The voltage to the input terminals of the receiver was adjusted to that which produced 110 dB SPL at 0.8 kHz in the 2-cc cavity by the receiver working into a single earmold. The value obtained proved to be 0.66 volts. All subsequent coupler measurements were made with 0.66 volts across the terminals of the hearing-aid receiver. Measurements were made at 0.8, 1.2, 1.6, 2.0, 2.4, 2.8, 3.2, 3.6, 4.0, 4.4, 4.8, 5.2, 5.6, 6.0 and 6.4 kHz. These frequencies were chosen to give relatively close spacing in the high frequency region which was of greatest interest of this study.

The test order used appears in Table 1. For example, with earmold 1, the first measurement was taken from the coupler microphone, the second from the probe-tube microphone when the probe-tube tip was

TABLE I

TEST ORDER FOR MEASUREMENTS IN THE ZWISLOCKI COUPLER AND IN THE 2-cc CAVITY

	Order of Measurements			
Earmold	First	Second	Third	Fourth
1	M	B	0	5
2	B	0	5	M
3	0	5	M	B
4	5	M	B	0
5	M	B	0	5
6	B	0	5	M
7	0	5	M	B
8	5	M	B	0
9	M	B	0	5
10	B	0	5	M
11	0	5	M	B
12	5	M	B	0
13	M	B	0	5
14	B	0	5	M
15	0	5	M	B
16	5	M	B	0

*M - coupler microphone; B - probe tube 1 mm from the coupler bottom; 0 - probe tube at 0-mm position; 5 - probe tube at 5-mm position located 1 mm from the coupler bottom, the third when the probe-tube tip was at the 0-mm position, and the fourth measurement was taken with the probe-tube tip at the 5-mm position. The sequence was ordered so that each condition appeared in each ordinal position an equal number of times.

Alternate Binaural Loudness Balances

Each subject was seated in a chair with his unoccluded ear facing the loudspeaker. There was a distance of approximately 1 meter between the loudspeaker and the ear facing the loudspeaker. The chair could be rotated so the subject's left ear or his right ear was aimed at the loudspeaker.

After the subject was properly positioned in the chair with his head fixed securely in place, the previously-fabricated earmold for the ear not directed toward the loudspeaker was sealed in the ear with petroleum jelly. The subject was instructed to avoid head movements.

The supporting apparatus for the probe-tube adapters were maneuvered into positions near the pinnae. The probe tubing extending from the earmold was connected to one probe-tube adapter. The second adapter was connected to the probe tubing used in making the measurements at the tympanic membrane of the unoccluded ear.

Each subject was informed when the probe tube was going to be inserted into the open ear canal. Perry reported the approximate depth of the human adult ear canal is 24 mm (45). Zwislocki reported a median of 22.5 mm for seven ear canals (60). This information was utilized by the investigator to gauge the proximity of the probe tube to the tympanic membrane. At the start of the insertion procedure, the probe tip was aligned with the entrance to the ear canal. The millimeter scale on the micromanipulator was used to monitor the probe depth. The mean ear canal depth for the subjects was 21.9 mm (N=15) with a standard deviation of 1.66 mm. When the subject reported that the probe tip had touched the tympanic membrane, the distance was noted and then the micromanipulator was used to retract the probe tube a distance of 1 mm. Subjects' impressions of the eardrum contact event were generally characterized as a dull pain or a dull auditory sensation. Each subject, except for subject 3 in the first session, was positive in asserting that the tympanic membrane had been touched. The probe tube depth for this subject was 17 mm. Owing to the angling of the ear canal, the examiner was not able to insert the tube further without causing considerable discomfort to this one subject. No problems were experienced with the opposite ear of this subject or with either ear of any other subject.

Test signals. The frequencies used in the ABLB portion of the investigation were the same as those used in the coupler measurements discussed earlier. The signal generation and timing instrumentation which was described earlier in this chapter was used to produce pure-tone signals of 500 msec duration. The interstimulus intervals were also 500 msec. The rise and decay times of the signals were set by the electronic switches to be 50 msec. Hence, a 500 msec signal (including rise and decay times) was presented to the subject by the hearing-aid receiver followed by a silent interval of 500 msec. A 500 msec signal (including the rise and decay times) was then presented to the subject by the loudspeaker followed by a silent interval of 500 msec. This alternating paradigm was presented to the subject continuously until a loudness balance was made.

When the signal from the loudspeaker was used as the reference signal, the probe tube, inserted in the open ear canal in the manner previously described, and its associated instrumentation were employed to adjust the sound pressure level at the eardrum to 65 dB. The loudness balance was then carried out. The voltage, across the receiver's terminals, which produced the signal judged to be equal in loudness to the reference signal was recorded. In addition, the sound pressure level at the 0-mm probe-tube position (the comparison signal) was recorded. When the signal presented through the earmold was used as the reference signal, the level in the ear canal (at the earmold tip) was adjusted to 65 dB SPL. The voltage necessary to produce this signal was recorded. Then the subject carried out the loudness balance by adjusting the signal from the loudspeaker. With the signal from the loudspeaker set at the level producing the equal loudness judgment, the sound pressure level at the eardrum was observed from the probe tube microphone assembly.

Subjects' Instructions. The subjects responded through the use of a tracking procedure. A recording attenuator was controlled by the subjects to vary the loudness of the comparison signal. The subject was instructed to adjust the loudness of the comparison signal alternately to a value just greater than and just less than the loudness of the reference signal presented to the opposite ear. In subsequent trials, the starting level of the comparison signal was alternately set at levels greater or lesser than that which would presumably result in an equal loudness balance. For each loudness balance, the subject adjusted the recording attenuator for approximately two minutes. The levels corresponding to the last eleven reversals of the subject's tracing were averaged. This average was taken as the level of the loudness balance. Each subject was read the following instructions:

> You will hear tones of the same frequency alternately from the loudspeaker to your ____ ear and from the receiver-earmold combination to your ____ ear. Listen closely to the tone in your ____ ear and attempt to maintain the same loudness in your ____ ear by manipulating this switch. When the sound in your ____ ear grows louder than the sound in your ____ ear, throw the switch to the position marked softer and hold it until the sound is too soft to maintain equal loudness. At this point, throw the switch to the position labeled louder. Continue this procedure until the tones are turned on again. Listen only to the loudness of the signals and please disregard any other factors such as pitch or quality. Periodically during the test session you will hear continuous tones. The experimenter is measuring these signals during these periods; ignore them. Do you have any questions?

Virtually all of the subjects' questions were answered in the initial (practice) session.

ABLB test order. Each subject participated in three loudness-balance sessions on three different days. The first session lasted approximately 75 minutes and was devoted exclusively to practice. Subjects were trained until they appeared to understand the task thoroughly, until the excursions they produced on the recording attenuator were less than 10 dB, and until repeatable results were obtained (trial to trial differences of 5 dB or less). Three frequencies were arbitrarily selected for practice runs. In all other respects, the practice sessions were conducted in a manner identical to the two data collection sessions. No more than ten days separated any of the three sessions and most were held within five days of one another.

Subjects carried out loudness balances at each of the test frequencies which were presented and in the order shown in Table 2. There were four binaural conditions as follows: condition A wherein the reference signal was presented to a subject's right ear by the loudspeaker with the comparison signal presented to the left by the hearing aid

TABLE 2

SEQUENCES OF FREQUENCY PRESENTATION IN THE
ALTERNATE BINAURAL LOUDNESS BALANCES

Subject	Session	Frequency order
1	1	0.8 to 6.4 kHz
1	2	3.6 to 6.4 kHz; 0.8 to 3.2 kHz
2	1	6.4 to 0.8 kHz
2	2	3.2 to 0.8 kHz; 6.4 to 3.6 kHz
3	1	3.6 to 6.4 kHz; 0.8 to 3.2 kHz
3	2	0.8 to 6.4 kHz
4	1	3.2 to 0.8 kHz; 6.4 to 3.6 kHz
4	2	6.4 to 0.8 kHz
5	1	3.6 to 6.4 kHz; 0.8 to 3.2 kHz
5	2	0.8 to 6.4 kHz
6	1	3.2 to 0.8 kHz; 6.4 to 3.6 kHz
6	2	6.4 to 0.8 kHz
7	1	0.8 to 6.4 kHz
7	2	3.6 to 6.4 kHz; 0.8 to 3.2 kHz
8	1	6.4 to 0.8 kHz
8	2	3.2 to 0.8 kHz; 6.4 to 3.6 kHz

receiver and earmold; condition B wherein the reference signal was presented to the subject's right ear by the receiver-earmold with the comparison signal presented to the left ear by the loudspeaker; condition C wherein the reference signal was presented to the subject's left ear by the loudspeaker and the comparison to the right ear by the receiver-earmold; and condition D wherein the reference signal was presented to the subject's left ear through the receiver-earmold and the comparison signal was presented to the right ear by the loudspeaker. The odd-numbered subjects participated in conditions A and B while the even-numbered subjects participated in conditions C and D. Hence, for the odd-numbered subjects, reference signal was directed to the right ear, but the transducers were reversed in the two sessions. The even-numbered subjects received the complement of these conditions. This sequence is summarized in Table 3.

Sound Pressure Level Measurements at the 0-mm and the 5-mm Positions

Following the ABLB procedure, sound pressure level measurements were made at the 0-mm and the 5-mm positions in the right ears of four subjects and in the left ears of four subjects. The hearing-aid receiver was driven with 0.016 volts appearing across its input terminals. The test frequencies were the same as in the coupler measurements and in the ABLB measurements. For the data collection, subjects were seated in the dental chair with their heads securely fixed by the holding apparatus previously described. For both the 0-mm and the 5-mm positions, the earmold was reseated in the ear canal and sealed with petroleum jelly. For four subjects, the experimenter increased frequency in the test intervals

TABLE 3

ORDERING OF ABLB TEST CONDITIONS*

Subject	Session 1	Session 2
1	A	B
2	C	D
3	B	A
4	D	C
5	A	B
6	C	D
7	B	A
8	D	C

*For meaning of A, B, C, and D see text.

from 0.8 kHz to 6.4 kHz for the 0-mm position and then decreased frequency in the test intervals from 6.4 kHz to 0.8 kHz for the 5-mm position. The complement of this test order was used for the other four subjects. For subjects 2, 4, 6, and 8, the 5-mm data were obtained first.

CHAPTER IV

RESULTS AND DISCUSSION

Preliminary Measurements

Measurements were made from the coupler microphones with the probe tube in place in each coupler at each of three probe-tube positions (0 mm beyond the earmold tip, 5 mm beyond the earmold tip and 1 mm away from the coupler bottom). For each probe-tube position, measurements were made both with the probe-tube aperture occluded with modeling clay and with the probe-tube aperture open. Finally, measurements were made from the coupler microphones when the probe tube was absent. In this instance, the probe-tube's drill hole was occluded with modeling clay. These measurements showed that the presence of the probe tube or its location in the cavity had no effect of practical significance upon the sound pressure level at the coupler microphone diaphragms.

Additionally, measurements were made with the probe-tube microphone while the probe tube was in place at each of the three positions. Also, measurements were made from the probe-tube microphone with the probe-tube tip in place at each of the three positions but with its aperture occluded. Blocking the probe tube aperture reduced the sound pressure reaching the probe-tube microphone by not less than 27 dB for the frequencies studied, thereby demonstrating that the sound transmission through the walls of the tubing used (or through other pathways) did not significantly affect the probe-tube readings obtained with the normally-open tube.

Results of Coupler Measurements

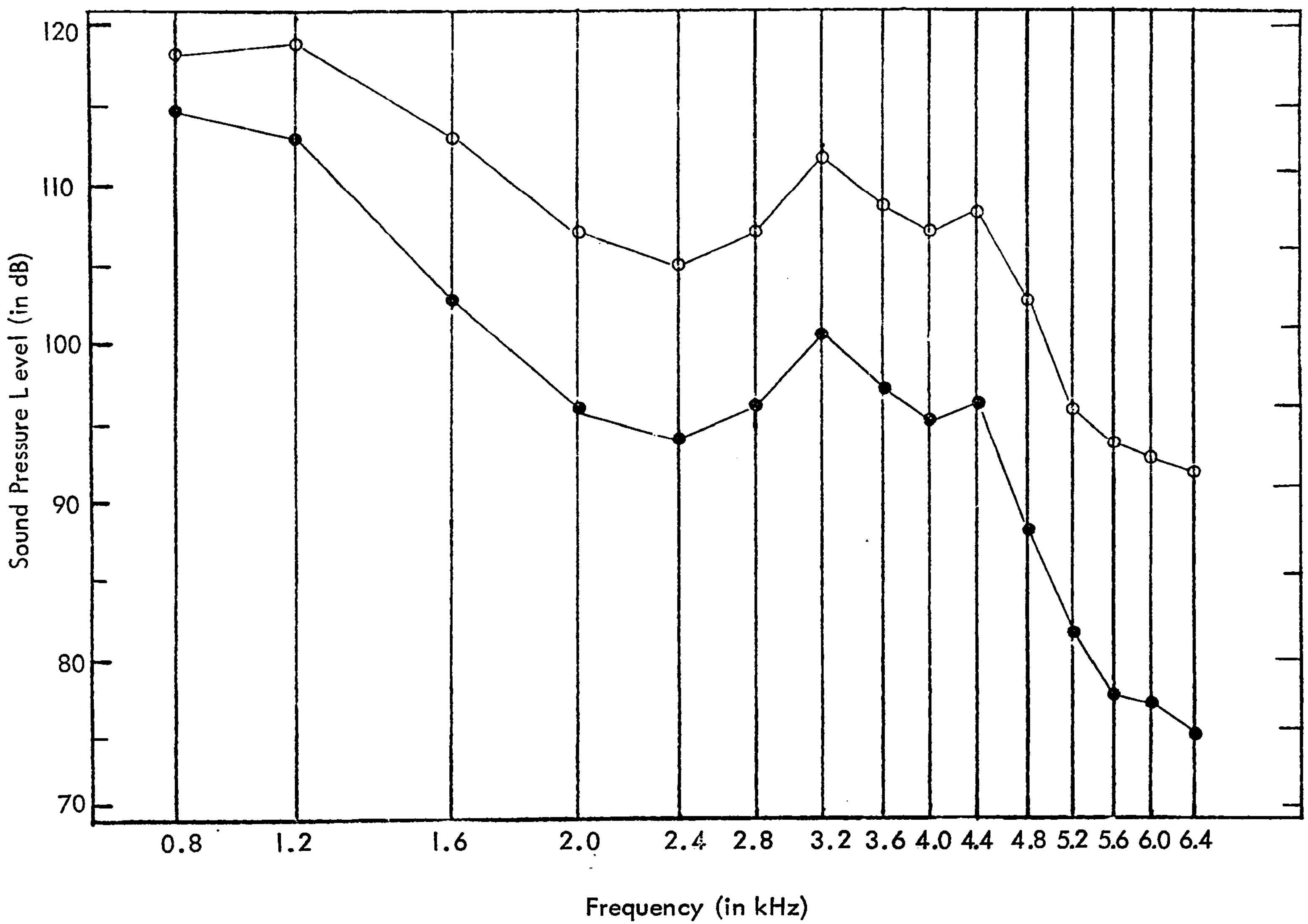
Sound pressure level measurements were made utilizing the probe-tube instrumentation assemblage at three positions in the 2-cc cavity and in the Zwislocki coupler. The data obtained at each position were compared with those obtained at each of the other positions and with the levels developed at the analogous positions in the ear canals. One set of measurements was made with the probe tube positioned 1 mm from the coupler microphone. The second set of measurements was made by a probe tube placed at the tip of the earmold (0-mm position). The third set was made with the probe tube terminus at a point 5 mm beyond the earmold tip (5-mm position).

Coupler Microphone Measurements

Figure 8 records the mean frequency-response data for the hearing-aid receiver-earmold system recorded from the microphones in the 2-cc cavity and in the Zwislocki coupler. The mean data appear in tabular form in Appendix I. There is a substantial decrease in level in each coupler from 0.8 kHz to 2.0 kHz. From 2.0 kHz to 4.4 kHz the system's frequency response is essentially flat. This flat region is followed by diminished sound pressure levels through 4.8 to 6.4 kHz.

The similarity of the general configuration of the curves shown in Figure 8 may be explained on the basis of various common elements in the two measurement situations comprising the sound input system. These common elements include the receiver, the volume of air over the receiver's

Figure 8. Mean sound pressure levels taken from the coupler microphones of the 2-cc and the Zwislocki couplers with a constant voltage input to the receiver. The open circles represent the data for the Zwislocki coupler while the closed circles represent the data for the 2-cc cavity.


Sound Pressure Level (in dB)
120
110
100
90
80
70
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

diaphragm, and the recess volume of the device which coupled the receiver's nubbin to the sound-inlet tubing (10,19,30,31,32,33,34,51,59). The concern of this investigation, however, was with the differences between the frequency response curves observed in the two couplers.

The levels developed in the 2-cc cavity fall farther and farther below those in the Zwislocki coupler as frequency is increased. This is illustrated more clearly in Figure 9. The slope of the 2-cc cavity data, plotted relative to that from the Zwislocki coupler, is such that it can be fit fairly well with a straight line with a slope of -4.3 dB per octave.

Figure 9 also provides a comparison of the 2-cc cavity - Zwislocki coupler differences observed in this study with these same differences observed by Sachs and Burkhard (50). Good agreement between the results of the two investigations is seen.

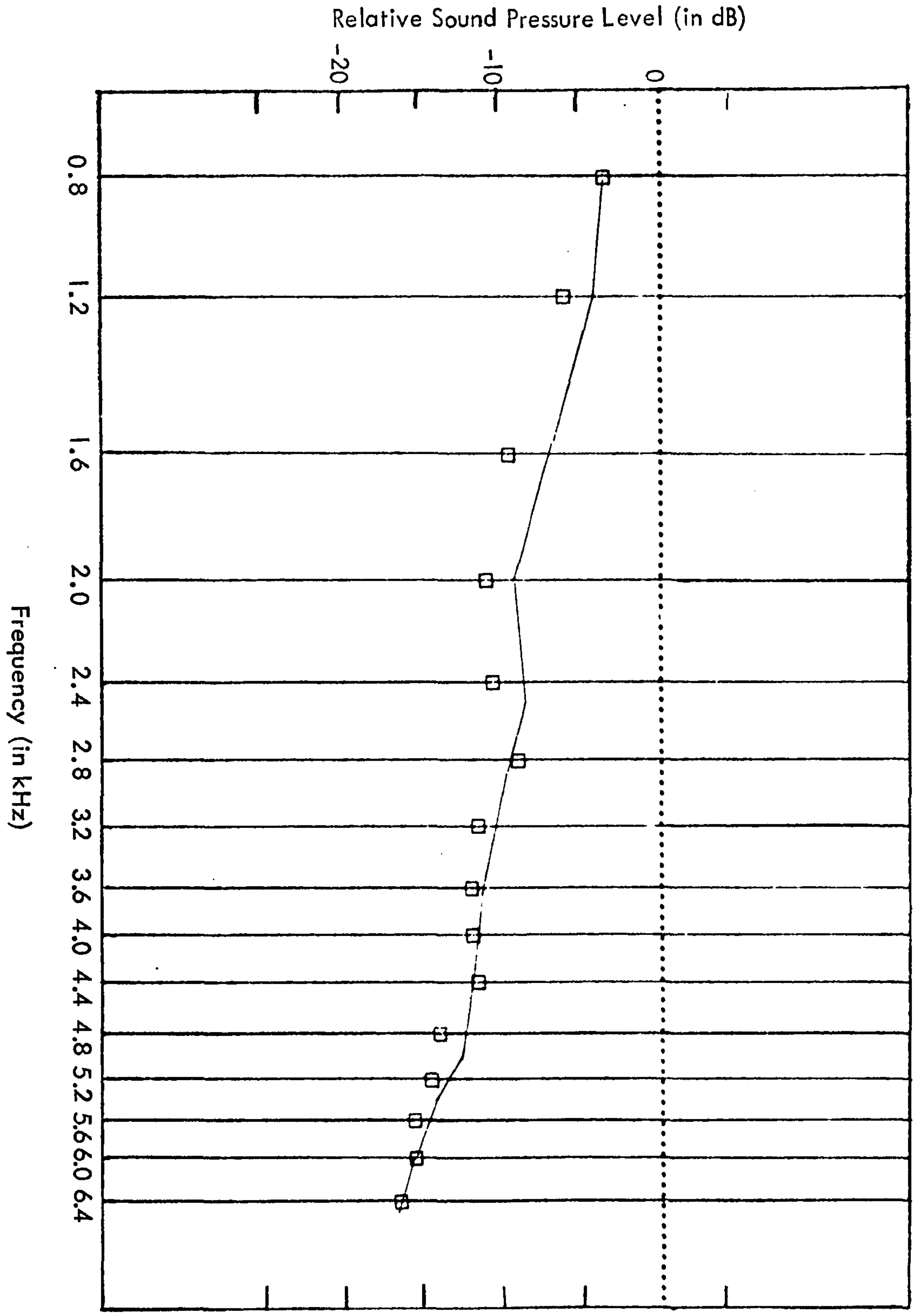
The inter-earmold variability for the measurements taken in the two couplers is reported in Table 4. The variability between earmolds is essentially the same for the data from the two couplers although there is a slight trend for larger standard deviations for the measurements made in the Zwislocki coupler.

Probe-Tube Measurements in the Couplers

The mean sound pressure levels recorded from the probe-tube instrumentation at the 0-mm, 5-mm, and the 1-mm from-the-bottom probe-tube positions for the two couplers appear in Figures 10 and 11. Inter-earmold standard deviations for these data appear in Table 5. The mean data for these measurements are listed in Appendix II.

The data plotted in Figures 10 and 11 are the differences (in dB) observed between the levels at the diaphragm of the probe-tube

Figure 9. Sound pressure levels recorded from the coupler microphone in the 2-cc cavity relative to the levels recorded from the coupler microphone in the Zwislocki coupler for this investigation and for the investigation of Sachs and Burkhard (50). The solid line represents data interpolated from Sach's and Burkhard's Figure 1 and the squares represent the data for the current study.



Relative Sound Pressure Level (in dB)
-20
-10
0
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

TABLE 4

STANDARD DEVIATIONS FOR THE SOUND LEVELS OBTAINED IN THE 2-cc CAVITY AND THE ZWISLOCKI COUPLER ACROSS FREQUENCY AS MEASURED FROM THE COUPLER MICROPHONES (N=16)

Frequency kHz	2-cc cavity S.D.	Zwislocki coupler S.D.
0.8	1.91	0.74
1.2	1.21	0.76
1.6	0.81	0.98
2.0	0.54	1.04
2.4	0.53	0.96
2.8	0.26	0.85
3.2	0.60	0.94
3.6	0.72	0.91
4.0	0.88	1.01
4.4	0.68	0.79
4.8	1.09	1.62
5.2	0.95	1.25
5.6	0.59	1.42
6.0	0.68	1.22
6.4	0.88	1.30

Figure 10. The mean sound pressure level recorded at the diaphragm of the probe-tube microphone plotted relative to the level at the coupler microphone at each frequency for each of the three probe-tube positions in the 2-cc cavity. The open squares represent the data for the measurements made 1 mm from the coupler bottom, the closed circles represent the measurements made at the 5-mm position, and the open circles represent the measurements made at the 0-mm position.

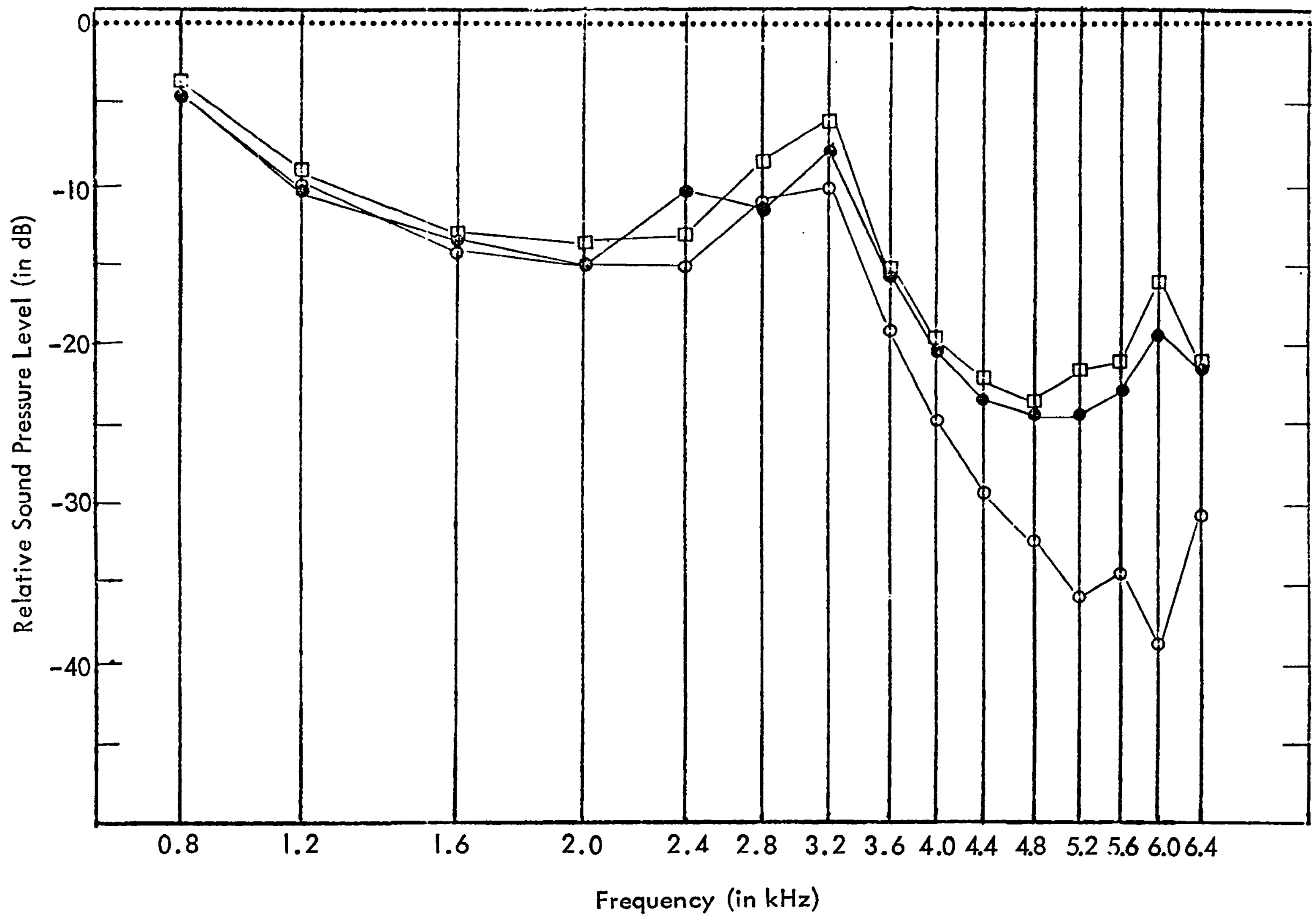

0
-10
-20
-30
-40
Relative Sound Pressure Level (in dB)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 11. The mean sound pressure level recorded at the diaphragm of the probe-tube microphone plotted relative to the level at the coupler microphone at each frequency for each of the three probe-tube positions in the Zwislocki coupler. The open squares represent the data for the measurements made 1 mm from the coupler bottom, the closed circles represent the measurements made at the 5-mm position, and the open circles represent the measurements made at the 0-mm position.

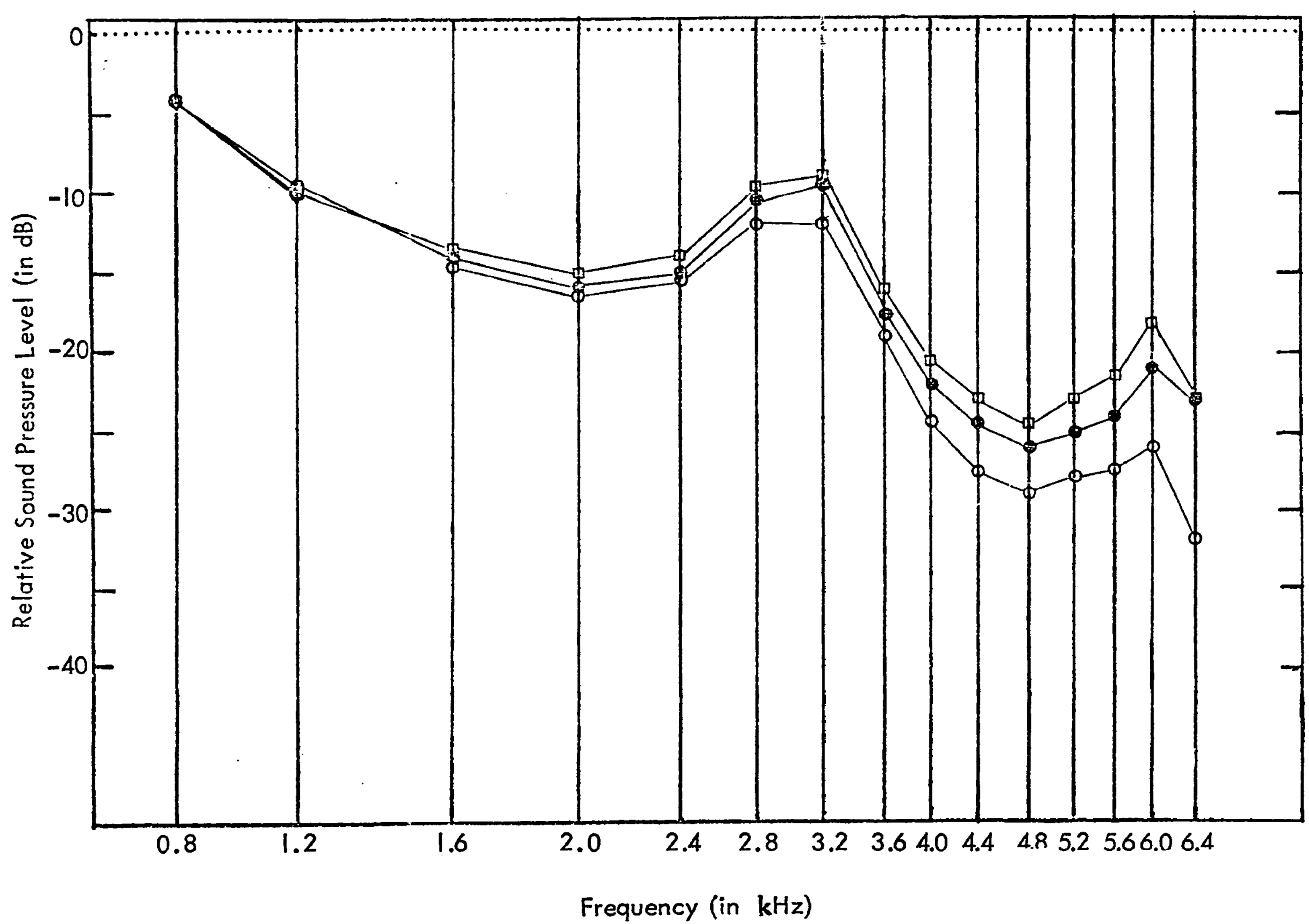

Relative Sound Pressure Level (in dB)
0
-10
-20
-30
-40
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

TABLE 5

INTER-EARMOLD STANDARD DEVIATIONS (in dB), BY FREQUENCY, FOR PROBE-TUBE MEASUREMENTS IN THE 2-cc CAVITY AND IN THE ZWISLOCKI COUPLER (N=16)

	2-cc cavity			Zwislocki Coupler		
kHz	1 mm bottom	5 mm	0 mm	1 mm bottom	5 mm	0 mm
0.8	1.19	1.50	1.25	1.01	1.17	0.30
1.2	0.93	0.86	1.30	0.86	0.44	0.55
1.6	0.74	0.60	0.87	1.12	0.75	0.52
2.0	0.68	0.44	0.50	0.80	0.44	0.44
2.4	0.60	0.61	0.43	0.74	0.56	0.70
2.8	0.68	1.03	0.82	0.88	0.81	0.62
3.2	0.72	0.53	0.70	1.02	0.80	0.91
3.6	0.85	0.55	0.92	0.75	0.93	0.96
4.0	0.98	1.04	1.21	0.94	1.25	0.83
4.4	0.56	0.94	1.51	1.06	1.26	0.81
4.8	0.83	1.38	1.78	1.25	1.09	1.30
5.2	0.82	1.16	2.55	1.11	0.95	1.40
5.6	0.93	1.06	2.01	1.17	0.98	1.54
6.0	0.80	1.02	1.35	0.97	1.14	1.35
6.4	1.06	1.38	1.99	1.34	1.40	1.09

microphone and those observed at the coupler microphone at the same frequency and the same input voltage to the hearing-aid receiver.

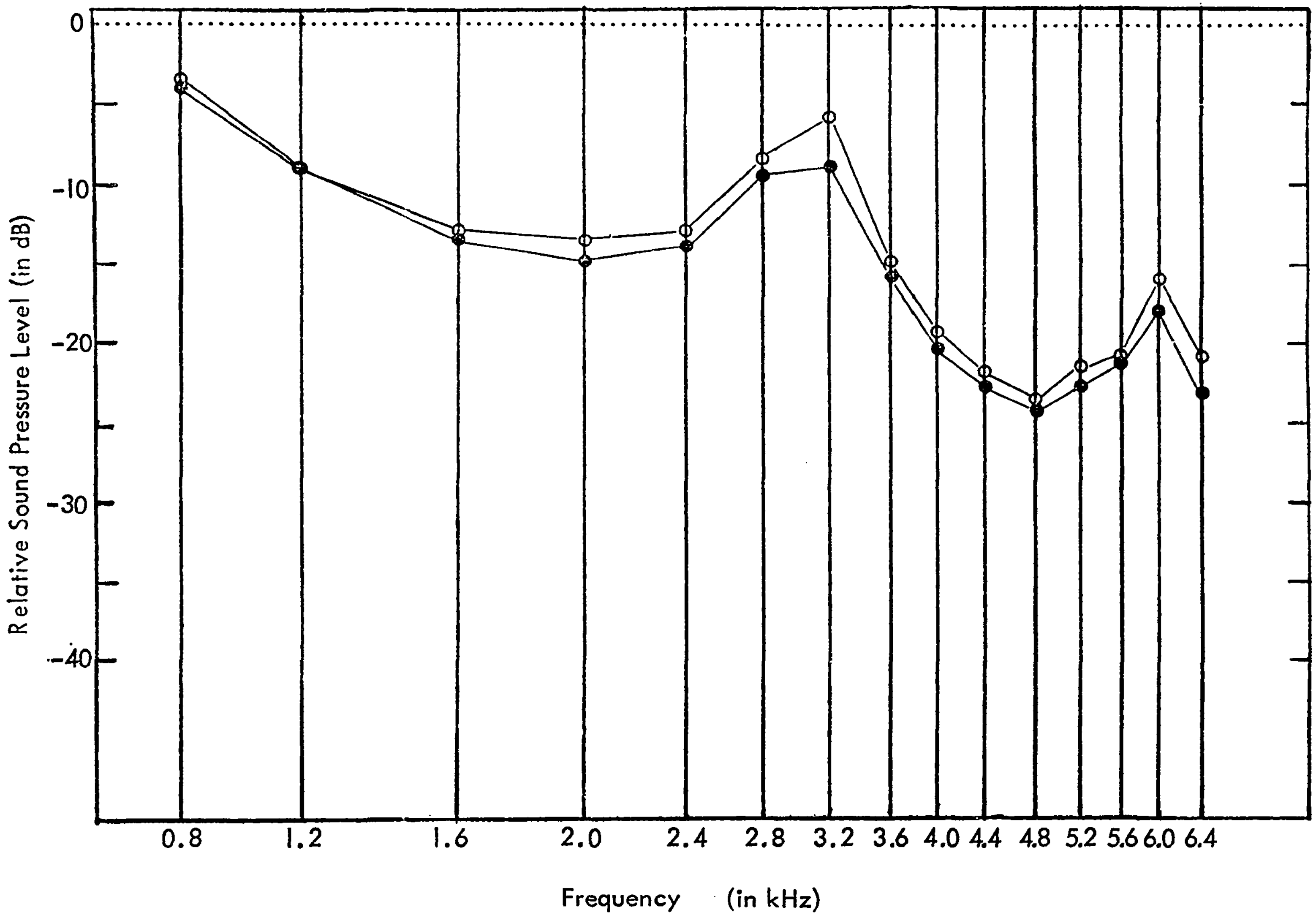
As expected, the levels at the probe-tube microphone decrease relative to those at the coupler microphone in each coupler as frequency is increased. It should be noted that the levels at the highest frequencies do not drop to the extremely low values usually observed with hearing-aid receivers because the data is recorded relatively (i.e., i.e., probe tube-microphone data re coupler microphone data).

In Figure 10, which records the results from the 2-cc cavity, there appear to be no differences of a systematic nature among the mean sound pressure levels measured at the three probe-tube positions from 0.8 to 2.8 kHz. Starting at 2.8 kHz, the curve representing measurements at the 0-mm position diverges from the curves representing measurements made 1 mm from the coupler bottom and at the 5-mm position. Sound pressure levels observed at the 0-mm position are distinctly different from either of the other two sets of data in the range from 4.4 kHz to 6.4 kHz.

Figure 11 reports data obtained in a similar manner with the Zwislocki coupler. Again, through 2.8 kHz the levels recorded at the three positions are essentially identical. Above that frequency, levels recorded at the 5-mm position are only slightly less than those recorded 1 mm from the coupler bottom. Although the differences are not as large as observed in the 2-cc cavity, the levels recorded at the 0-mm position are discrepant from the levels recorded for the other two positions above 2.8 kHz.

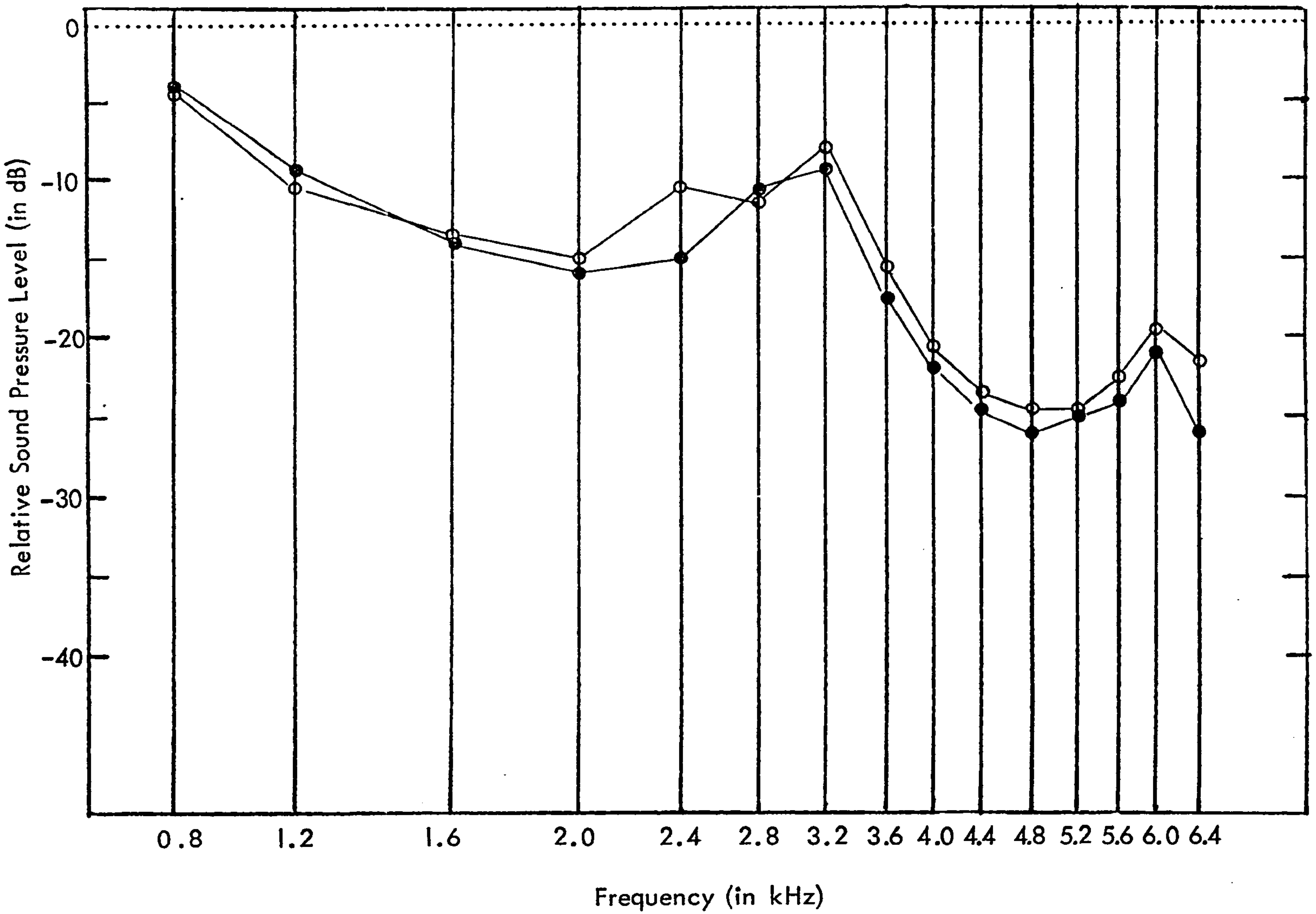
Figures 12, 13, and 14 compare and describe the acoustic performance differences between the two couplers based on measurements at

Figure 12. The mean sound pressure level recorded by the probe-tube microphone when located 1 mm from the coupler bottom in each of the two couplers plotted relative to the level at the respective coupler microphones at each frequency. The open circles represent the data for the 2-cc cavity and the closed circles represent the data for the Zwislocki coupler.



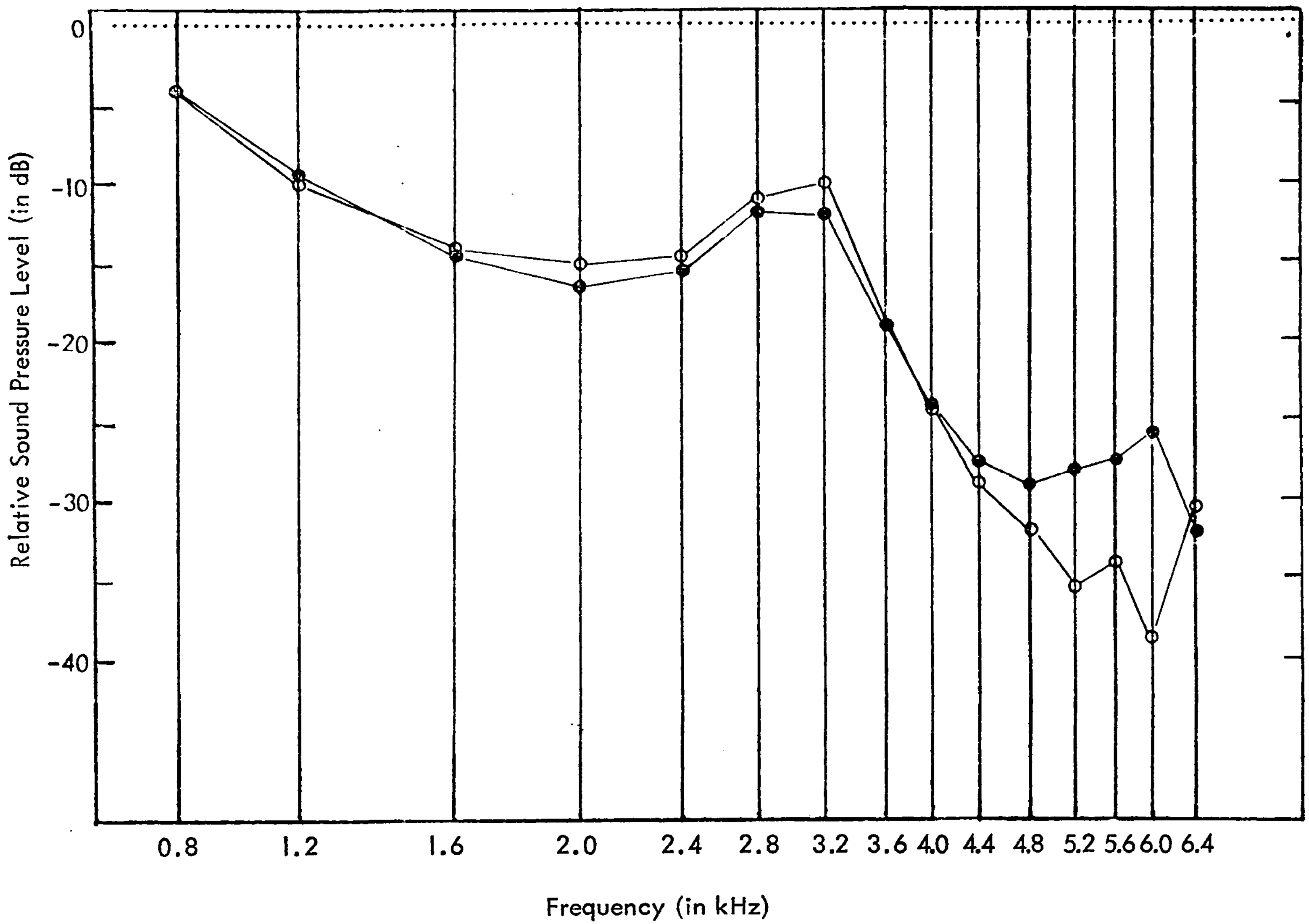
Relative Sound Pressure Level (in dB)
0
-10
-20
-30
-40
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 13. The mean sound pressure level at the 5-mm position in each of the couplers plotted relative to the level recorded from the respective coupler microphones at each frequency. The open circles represent the data for the 2-cc cavity and the closed circles represent the data for the Zwislocki coupler.



Relative Sound Pressure Level (in dB)
0
-10
-20
-30
-40
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 14. The mean sound pressure level at the 0-mm position in each of the couplers plotted relative to the level recorded from the respective coupler microphone at each frequency. The open circles represent the data for the 2-cc cavity and the closed circles represent the data for the Zwislocki coupler.


0
-10
-20
-30
-40
Relative Sound Pressure Level (in dB)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

each of the three probe-tube positions. The curves in these three figures are the same curves as those in Figures 10 and 11. Figure 12 compares the results for the 1 mm from-the-coupler bottom position obtained in the two couplers. The sound levels recorded in the two couplers are nearly identical. In Figure 13 which contrasts the results obtained at the 5-mm position, the two curves are virtually indistinguishable except for a slight difference at 2.4 and 6.4 kHz. Figure 14 shows slight coupler differences under the 0-mm-measurement condition in the range from 2.0 to 3.2 kHz, but substantial coupler differences are seen at and above 4.8 kHz.

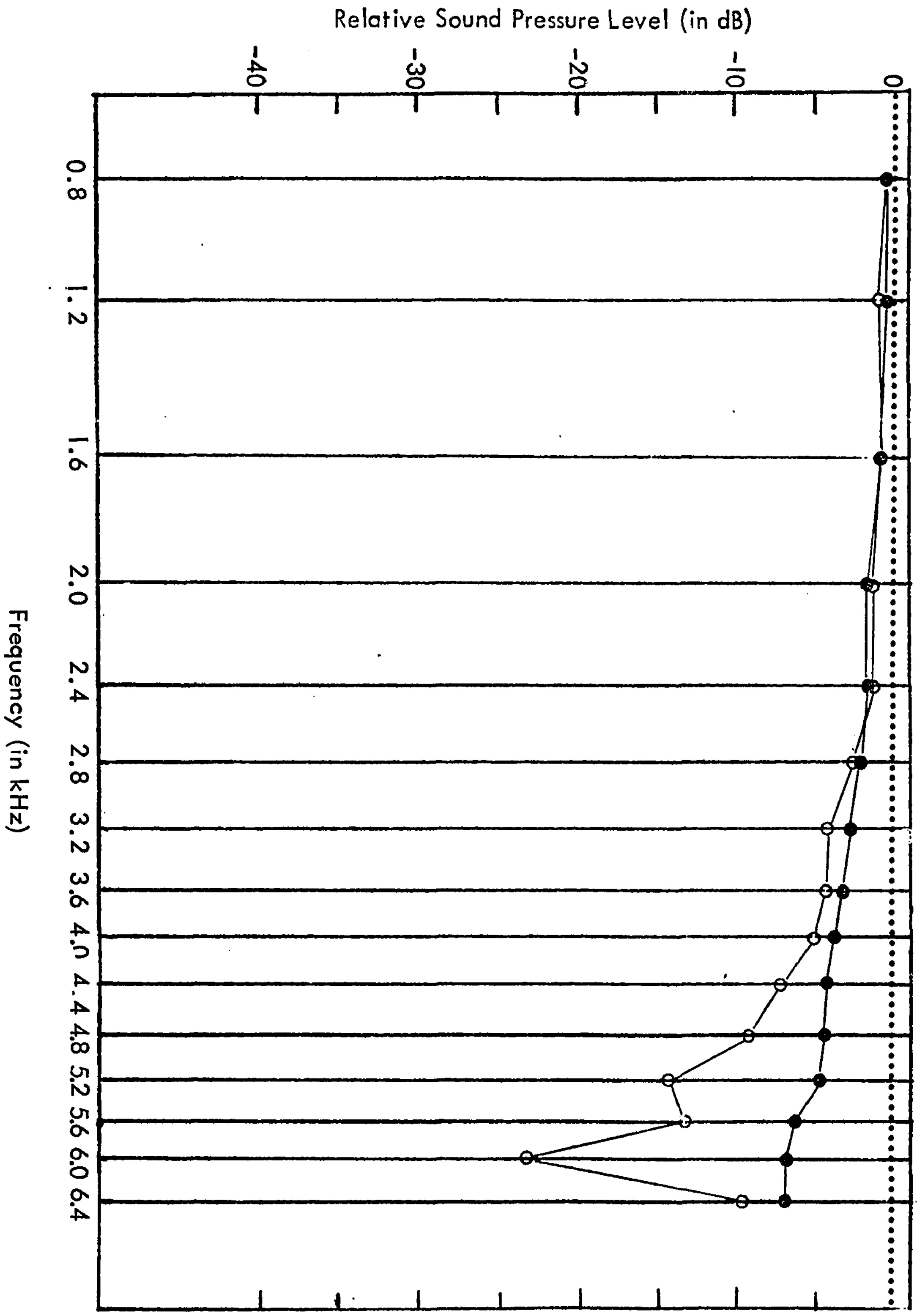
The data presented and compared in the five previous figures indicate that measurements made at points proximal to the sound-inlet bore differ from those sound pressures measured at the bottom of the cavity. Sachs and Burkhard (49) previously observed this effect. They explained their observations on the basis of Ingard's (21) theory of the radiation of sound in cylindrical cavities. For low frequencies, they reasoned, the reactance of a cavity is negative. For sound pressures near the sound-inlet tube there is a positive reactance (or inertance). It follows, as they point out, that the total transfer reactance will be zero at some particular frequency at particular locations in the cavity. Then, the sound pressure level will be substantially lower. This frequency is called f_0 by Sachs and Burkhard. As measurements are made at points farther away from the sound-inlet tube, the frequency of f_0 increases. They state that as a function of frequency the locations of diminished sound pressure in a circular cavity are determined by several geometric parameters. The most important of these are the ratio of the sound-inlet tube's diameter to cavity diameter and the ratio of the diameter of the cavity to length of the cavity. Because this is true, it follows that the frequency regions of diminished sound pressure levels would not be the same for identical locations (relative to the ear-mold) in cavities of dissimilar size or configuration and/or cavities having dissimilar sound-inlet tube diameters.

In an attempt to further evaluate these data in terms of Sachs' and Burkhard's application of Ingard's theory, the author communicated with R.M. Sachs who, together with Burkhard, had previously developed a computer program which evaluates the transfer impedance of a cylindrical closed cavity with arbitrary dimensions (47). Provided with dimensional data pertinent to the couplers and the associated sound-inlet tube and probe-tube systems used in this investigation, Sachs employed his program to evaluate the sound pressure distribution at the frequencies of interest in this investigation for the 2-cc cavity and for a cavity with the dimensions of the Zwislocki coupler.

Figure 15 shows the results obtained in this study for the 0-mm position plotted relative to the results observed at the 1-mm-from-the-coupler-bottom position in each coupler. For the Zwislocki coupler, the level at the 0-mm position relative to the level near the coupler bottom decreases as frequency increases at a slope of approximately 2 to 3 dB per octave. For the 2-cc cavity, the result is essentially equivalent to the Zwislocki coupler result through 4.0 kHz, but, at 6.0 kHz, an antiresonance of 20 dB occurs.

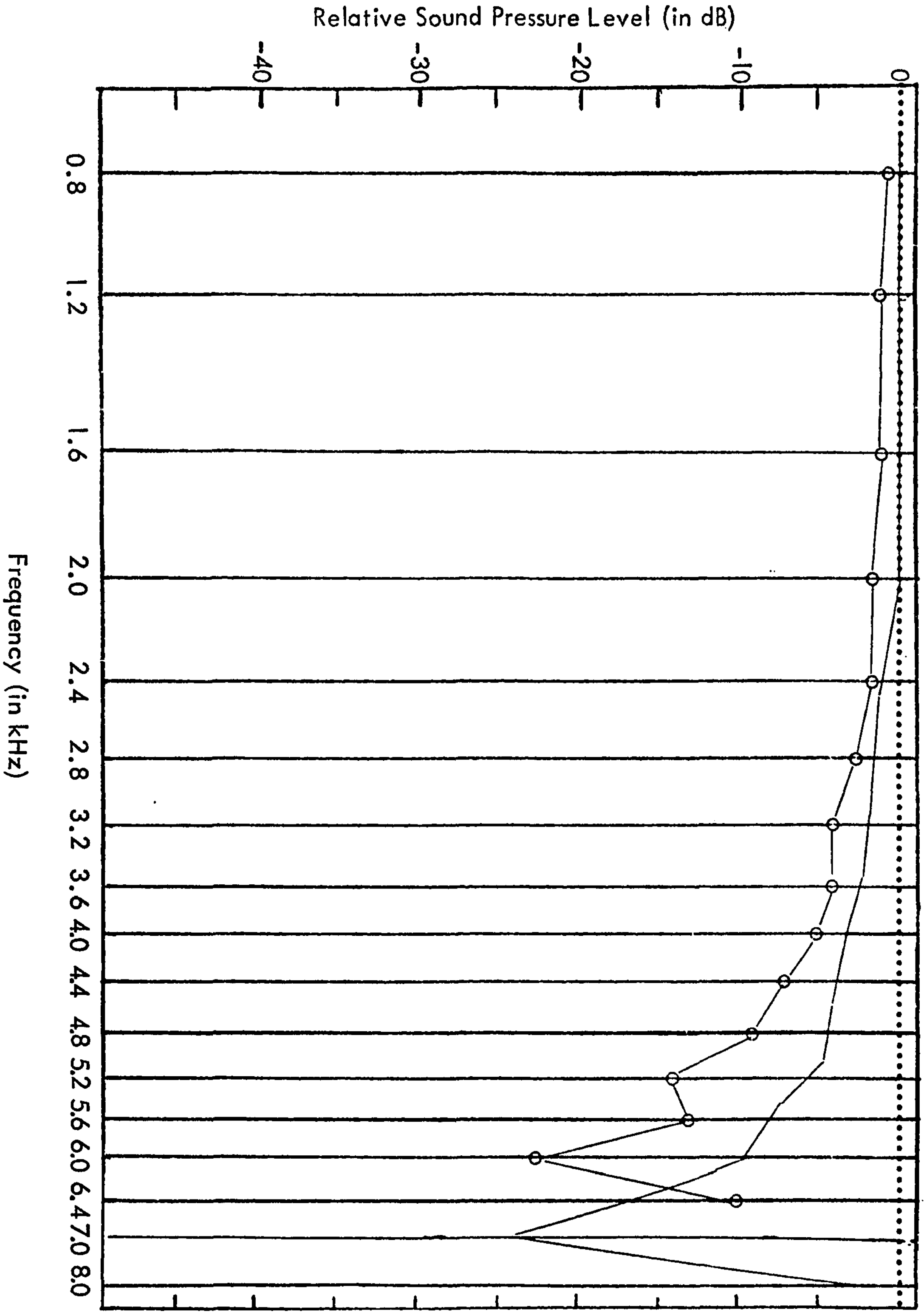
Figure 16 illustrates the obtained result from this study (Figure 15) for the 2-cc cavity and a comparable computer generated

Figure 15. The results obtained at the 0-mm position plotted relative to the results obtained 1 mm from the coupler bottom for the 2-cc cavity and for the Zwislocki coupler. The open circles represent the data for the 2-cc cavity and the closed circles represent the data for the Zwislocki coupler.



Relative Sound Pressure Level (in dB)
0
-10
-20
-30
-40
Frequency (in kHz)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4

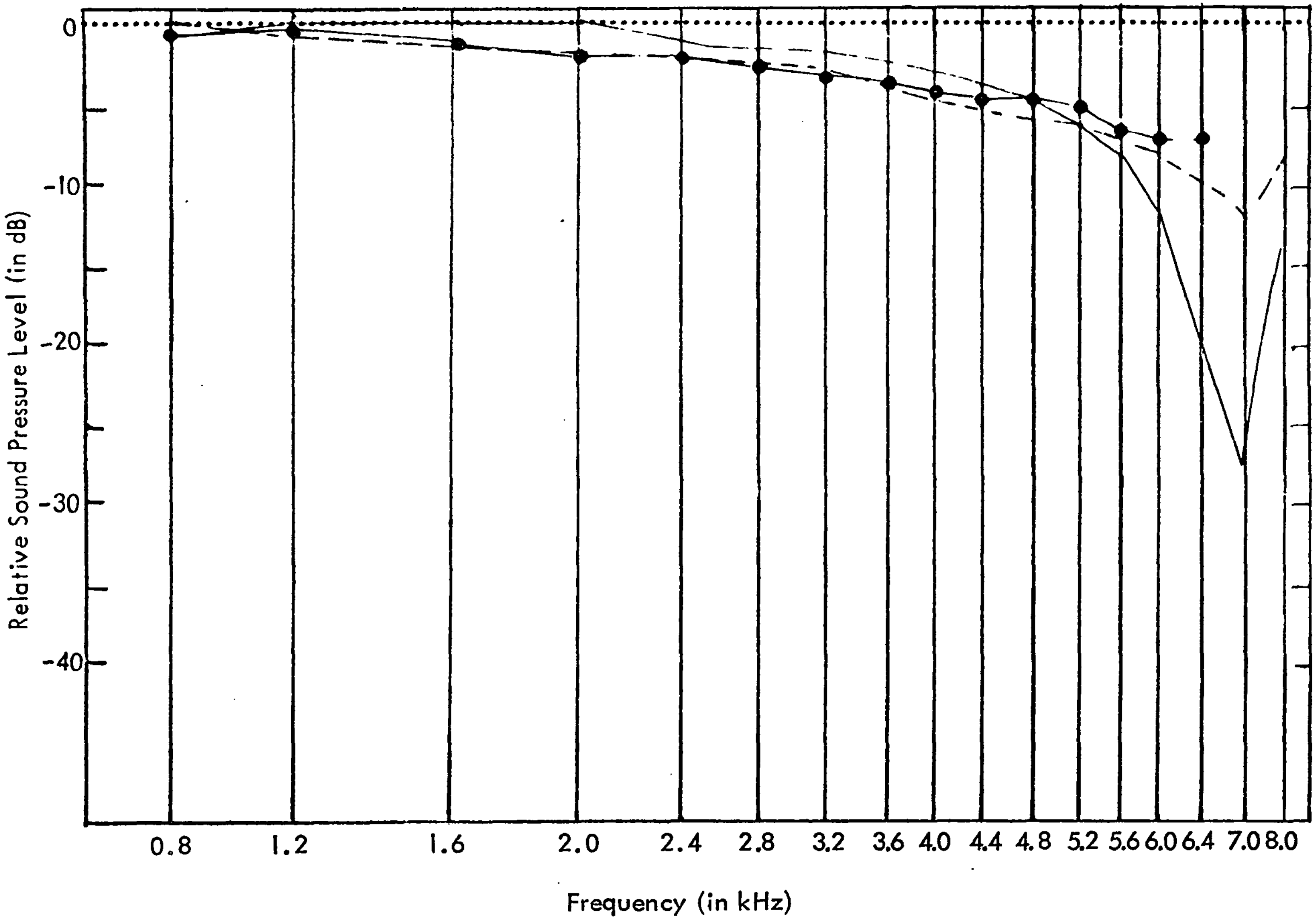
Figure 16. The results obtained at the 0-mm position plotted relative to the results obtained 1 mm from the coupler bottom for the 2-cc cavity and the theoretical result provided by Sachs (47). The solid line represents the theoretical result and the open circles represent the empirical results for the 2-cc cavity.


Relative Sound Pressure Level (in dB)
0
-10
-20
-30
-40
Frequency (in kHz)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
7.0
8.0

theoretical curve provided by Sachs (47). The antiresonant frequency for the obtained data occurs at 6.0 kHz. The theoretical antiresonance occurs at 7.0 kHz. The source of this discrepancy is not clear. However, it is noted that a change in the assumed distance between the probe-tube orifice and the sound-inlet tube orifice to a somewhat smaller value would shift the calculated antiresonance downward to that observed. Sachs (48), in a later communication, speculated that the slight difference between observed and theoretical results may be attributable to the fact that the sound-inlet tube was not located at the precise geometric center of the cavity.

Figure 17 depicts the theoretical result and the obtained result for the Zwislocki coupler. The figure also allows a comparison with data reported by Zwislocki (60). (Zwislocki's data points also represent the differences observed between measurements made in his coupler at a point corresponding to the tip of an earmold and at the coupler bottom, but he apparently made these measurements with the coupler placed in a soundfield.) The similarity between the three curves is obvious below 5.2 kHz. Zwislocki's data and the data of the present investigation are in good agreement at least through 6.0 kHz. A sharp antiresonance appears at 7.0 kHz for the theoretical curve. A lesser sound pressure drop is seen in Zwislocki's data. An antiresonance is not apparent in the results of this investigation. It will be recalled that Sach's data were generated assuming a simple hard-walled cavity having the dimensions of a Zwislocki coupler. No calculations were made by Sachs which incorporated the additional reactance and resistances which are part of the Zwislocki coupler's design. It is possible that a sound pressure drop would have

Figure 17. The results obtained at the 0-mm position plotted relative to the results obtained 1 mm from the coupler bottom for the Zwislocki coupler, the theoretical result provided by Sachs, and data reported by Zwislocki (60). The solid line represents the theoretical result, the dashed line was interpolated from Zwislocki's Figure 7, and the closed circles represent the data for the present investigation.


0
-10
-20
-30
-40
Relative Sound Pressure Level (in dB)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
7.0
8.0
Frequency (in kHz)

at some frequency greater than 6.4 kHz in the data of this study as it does in Zwislocki's data. However, it seems probable that the absence of the sound pressure drop, as well as the lesser sound pressure decrease seen in Zwislocki's data, occurs because of the substantial resistive component present in the Zwislocki coupler, a factor which was not included in the Sachs computer program. When the reactances cancel each other the presence of resistance prevents the sound pressure from falling to zero. The greater the resistive component of the coupler impedance, the more shallow the nulls will be.

Probe Tube Calibration

Because the probe-tube effects in the two couplers are more similar as the measurements are made at points nearer the coupler microphone and because the coupler microphone is analogous to the location of the tympanic membrane in the ear canal, subsequent probe-tube corrections used in this investigation were derived on the basis of the differences observed for each coupler between the sound pressure levels recorded by the probe tube 1 mm from the coupler bottom and the sound pressure levels recorded by the coupler microphone. These differences were averaged across the two couplers at each frequency. Figure 12 (page 58) displays the data which were averaged and Appendix III lists the correction values that were used.

The inter-earmold standard deviations reported in Table 5 (page 55) show very little systematic variation with frequency, but there was a tendency for the variability to become larger as frequency was increased. Overall, the measurements made in the 2-cc cavity at the

0-mm position are more variable than the measurements made at the other positions in the 2-cc cavity or at any of the three positions in the Zwislocki coupler. The standard deviations reported in Table 5 are slightly larger than those reported by Zachman (59) for a 0-mm condition for frequencies below 5.0 kHz. He reported a range of standard deviations from 0.2 to 0.83 dB.

Results of Ear Canal Measurements

Sound pressure levels were measured at three locations in the ear canals of each of the subjects. The resulting levels at each position were compared with each other and with the levels developed at the analogous positions in the couplers. One set of measurements involved an alternate binaural loudness balance procedure which allowed the sound level at a point 1 mm from the tympanic membrane of the ear in which the earmold was worn to be inferred from that level actually measured 1 mm from the tympanic membrane of the opposite ear. The second set of measurements was made by a probe tube placed at the tip of the earmold (0-mm position). The third set was made with the probe tube terminus at a point 5 mm beyond the earmold tip (5-mm position).

Obtaining the Sound Pressure Level 1 mm from the Tympanic Membrane of an Occluded Ear Canal

In two of the four experimental conditions involving the alternate binaural loudness balance procedure one ear of each of eight subjects received the reference signal from the loudspeaker while the comparison signal was delivered by the receiver-earmold combination to the contralateral ear (conditions A and C). In the other two conditions one ear of each of eight subjects received the reference signal from the earmold-receiver combination while the opposite ear received the comparison signal from the loudspeaker (conditions B and D). (See pages 38-40 for a detailed discussion of the procedure.)

Table 6 lists the medians and interquartile ranges for the comparison signal levels when set by the subjects at a level they judged to be equal in loudness to the reference signal in the opposite ear. These values have been corrected for the probe tube frequency response, the derivation of which is described on page 72. The means and inter-subject standard deviations for conditions A and C and B and D are listed in Appendix IV. The standard deviations are highly variable from frequency to frequency sometimes reaching very large values, particularly when the speaker served as the reference. The occurrence of these sporadic large values is the result of occasionally highly discrepant loudness balances. The effect of these values was to unduly influence the mean under particular measurement conditions. For this reason, the medians and interquartile ranges were thought to more accurately reflect the true circumstances and were used to describe the data. It may be noted, however, that the differences between the means (see Appendix IV) and the medians (Table 6) are less than 2.0 dB except at 2.8, 5.2, 5.6 and 6.4 kHz in conditions B and D and except at 4.8 and 5.2 kHz in conditions A and C.

The median data for conditions A and C (left hand column of Table 6) represent the median sound pressure levels of the comparison signals at equal loudness (these signals were measured with the probe-tube tip located at the tip of the earmold). A signal set at 65 dB SPL (measured by a probe tube) 1 mm from the contralateral tympanic membrane

TABLE 6

MEDIANS AND INTER-QUARTILE RANGES OF THE COMPARISON SIGNAL SPL WHICH ADJUDGED EQUALLY LOUD TO A 65 dB SPL SIGNAL IN THE OPPOSITE EAR*
(Corrected for Probe Tube Response)

	Conditions A and C		Conditions B and D	
kHz	Median	Interquartile Range	Median	Interquartile Range
0.8	66.1	61.6-69.0	66.5	64.5-67.4
1.2	64.1	61.1-69.2	63.5	61.5-65.4
1.6	69.1	66.6-71.4	64.2	61.8-66.0
2.0	66.4	61.0-68.8	61.9	60.2-63.5
2.4	66.9	63.8-70.0	62.2	60.3-63.6
2.8	66.3	59.9-70.6	65.6	61.3-66.2
3.2	65.7	64.1-66.8	68.1	62.6-68.8
3.6	71.3	64.1-72.2	67.3	63.8-69.5
4.0	68.2	64.6-72.8	64.5	60.1-68.9
4.4	65.4	64.8-71-3	67.8	63.2-71.0
4.8	66.9	65.0-71.0	71.3	68.1-72.6
5.2	60.3	57.6-78.6	72.9	69.0-74.6
5.6	63.1	58.1-76.4	67.6	64.0-76.0
6.0	64.6	62.0-67.2	67.2	64.2-69.6
6.4	62.6	60.7-65.2	67.1	65.3-74.0

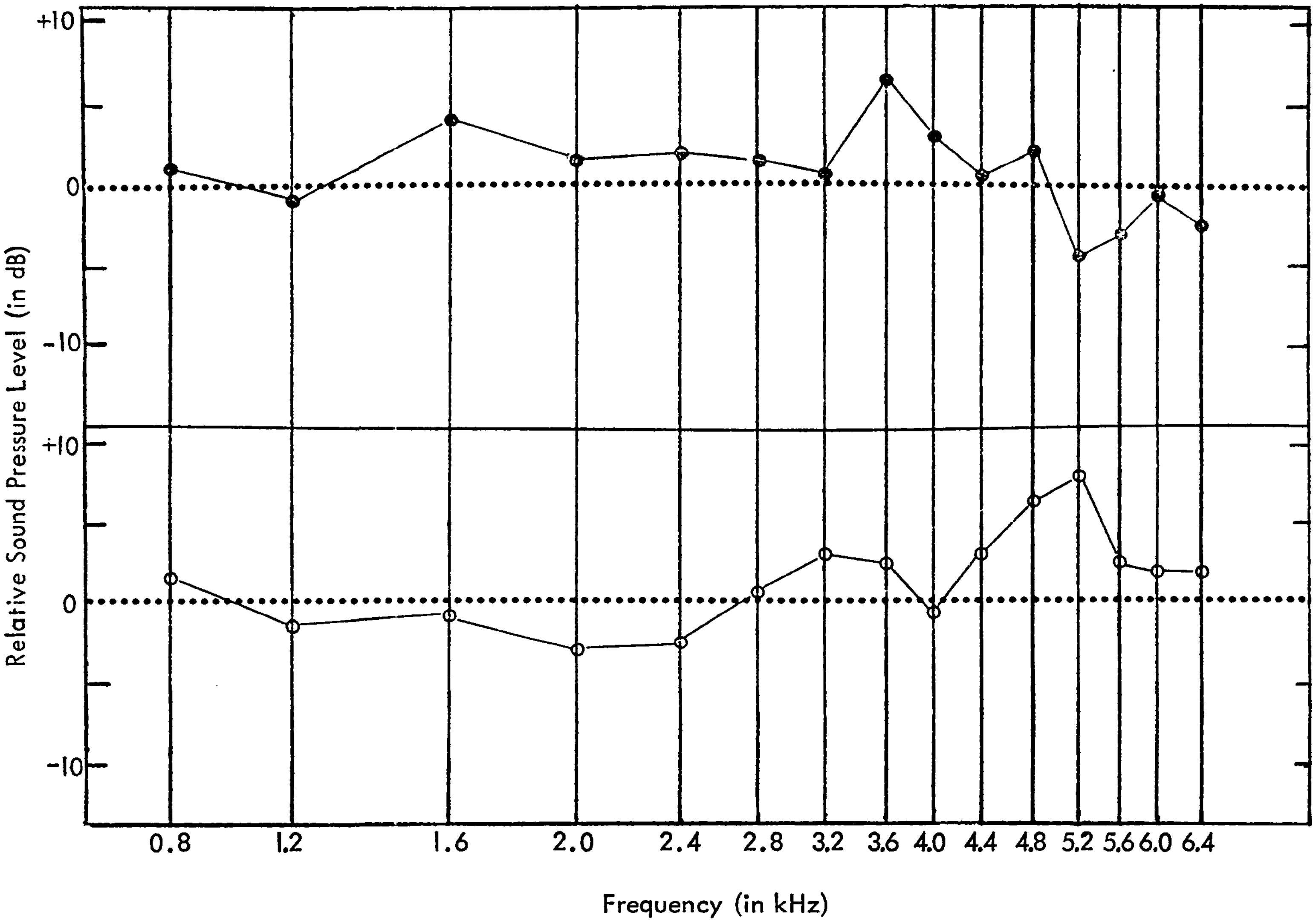
*When the reference was presented by the speaker, the level was set at 65 dB SPL 1 mm from the eardrum at each frequency. Conversely, when the reference was presented by the receiver, the level was set at 65 dB SPL at the earmold tip at each frequency.

served as the reference. The upper curve in Figure 18 shows the levels of the comparison signals plotted relative to the levels of the reference (65 dB SPL) at the tympanic membrane of the opposite ear.

The median data for conditions B and D (right hand column of Table 6) also represent the median sound pressure levels of the comparison signals at equal loudness (these signals were measured with a probe tube placed 1 mm from the tympanic membrane). A signal set at 65 dB SPL (measured by a probe tube) at the earmold tip in the ear canal of the contralateral ear served as the reference. The lower curve in Figure 18 shows the levels of the comparison signals plotted relative to the levels of the reference (65 dB SPL) at the earmold tip in the ear canal of the opposite ear.

The relationship of the comparison signal levels to the reference signal levels per se were not of particular interest in this investigation. Rather, the alternate binaural loudness balance procedure was used to establish the relationship between the levels at the tympanic membrane and those at the earmold tip. The lower curve in Figure 18, because the signal measured at the earmold tip served as the reference, conveniently illustrates the relationship between the levels at the tympanic membrane and those at the earmold tip for conditions B and D. In order to put the data for conditions A and C in the same form, three steps were taken. First, the differences shown in the upper portion of Figure 18 between the level at the earmold tip (the level of the comparison signal) and the 0 dB line (65 dB SPL at the opposite tympanic membrane) were noted for each frequency. Secondly, negative differences (values below the 0 dB line) were changed to positive differences and

Figure 18. Levels of the comparison signals relative to those of the reference signals at equal loudness. For the upper curve, the comparison signal was measured at the earmold tip (conditions A and C). For the lower curve, the comparison signal was measured 1 mm from the tympanic membrane (conditions B and D).

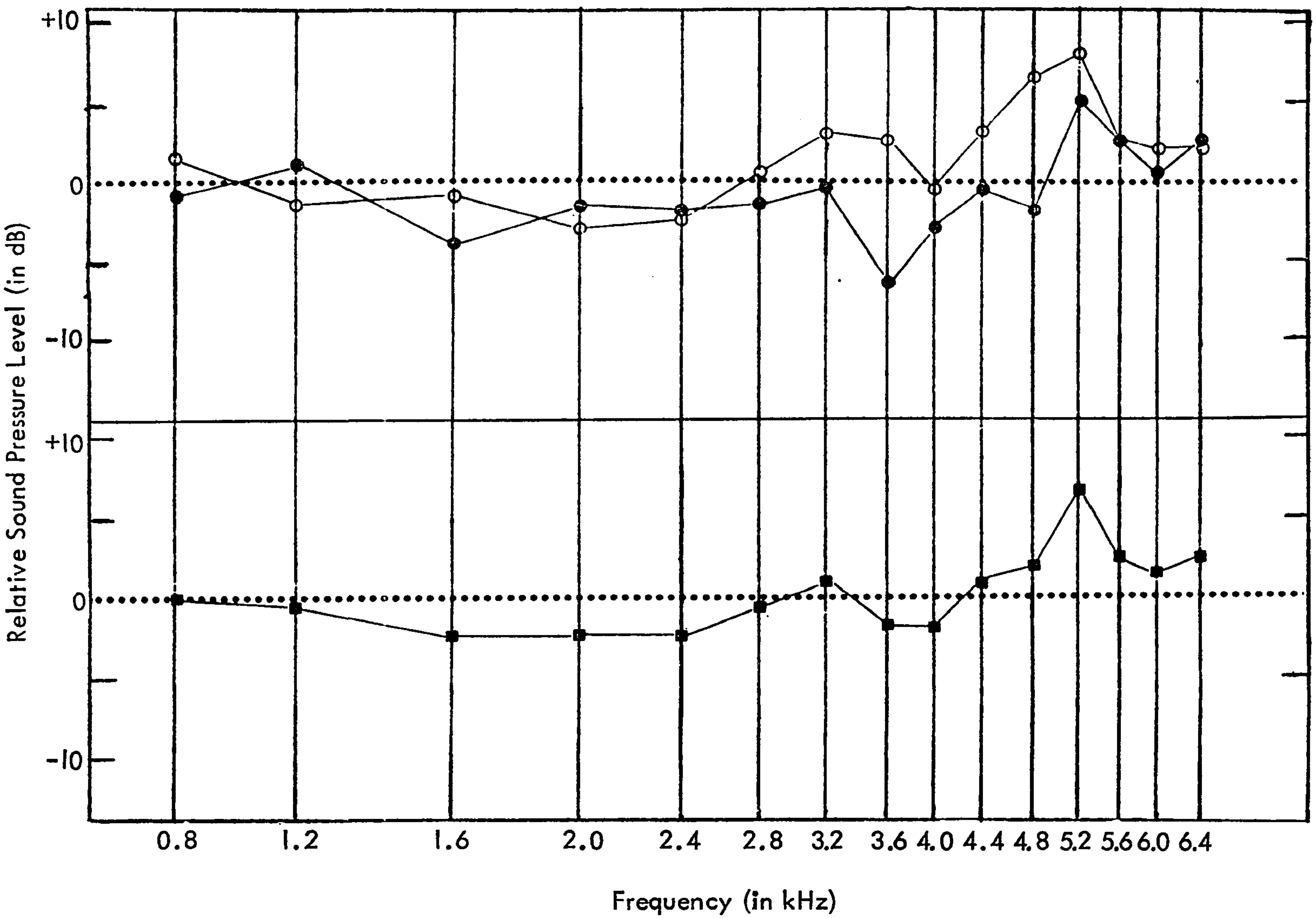

+10
0
-10
+10
0
-10
Relative Sound Pressure Level (in dB)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

positive differences (values above the 0 dB line) were changed to negative difference. Finally, after changing the sign for the value at each frequency, the data were replotted in the upper portion of Figure 19. For example, at 1.6 kHz the value above the 0 dB line was +3.5 dB. In the upper portion of Figure 19, the value was replotted as -3.5 dB. Therefore, at this frequency, when the level at the earmold tip was 65 dB SPL, the level at the tympanic membrane was 61.5 dB SPL.

The median levels at the tympanic membrane relative to the levels measured at the earmold tip at equal loudness (for conditions A and C and for conditions B and D) are plotted in the upper portion of Figure 19. The two values at each frequency were averaged in order to establish the average differences between the sound pressure levels 1 mm from the tympanic membrane relative to those at the earmold tip at equal loudness. At 1.6 kHz, for example, when the level of the reference signal at the earmold tip was 65 dB SPL, the level 1 mm from the tympanic membrane was 62.5 dB SPL. These differences are illustrated in the bottom portion of Figure 19 and will hereafter be referred to as the values for K.

The alternate binaural loudness balance data were used for deriving the frequency response of the receiver-earmold combinations at a position 1 mm from the tympanic membrane. (This procedure, of course, assumes that at equal loudness the sound pressure levels at the two tympanic membranes are equal.) As an intermediary step, the frequency response of the hearing-aid receiver at the earmold tip was derived. Then the values for K (representing the differences between the levels at the earmold tip and the levels at the tympanic membrane) were used to calculate the frequency response at the tympanic membrane.

Figure 19. Curves illustrating differences between median sound pressure levels measured at the earmold tip and at a position 1 mm from the tympanic membrane at equal loudness. All curves show the level at the tympanic membrane relative to that at the earmold tip. Open circles represent the data, in the same form previously plotted in the upper portion of Figure 18 after their signs were changed as described in the text.


Relative Sound Pressure Level (in dB)
+10
0
-10
+10
0
-10
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

The derivation involved the calculation of the sound pressure levels that would have been developed at the earmold tip by a constant voltage input to the hearing-aid receiver. Because these data were to be compared with data collected for the couplers, the voltage which drove the hearing-aid receiver in the coupler measurements was used. This value was 0.66 volts. The following formula summarizes the derivation of the hearing-aid receiver frequency response:

$$L_{EM} = 65 \text{ dB SPL} + 20 \log_{10} 0.66\text{v}/E$$

where L_{EM} is the derived sound pressure level at the earmold tip at a particular frequency with 0.66 volts impressed across the receiver's terminals. The value 65 dB SPL (the 0 dB line in the lower portion of Figure 19) represents the sound pressure level at the earmold tip produced by the voltage E. The values for E were calculated by noting the median voltage at each frequency in conditions B and D which developed a sound pressure level of 65 dB at the earmold tip together with the voltages noted for conditions A and C. However, because the median voltages observed in conditions A and C developed levels other than 65 dB SPL, the median voltages observed in the A and C conditions were transformed to the voltage that would have produced 65 dB SPL at the earmold tip. Then for each frequency, the median values for conditions B and D and the transformed median voltages for A and C were averaged. These averaged values for E are listed in Table 7. Finally, the ratios, in decibels, for $20 \log_{10} 0.66\text{v}/E$ were calculated and are listed in Table 7.

The sound pressure levels produced at the earmold by 0.66 volts were calculated by this formula. The SPL resulting from these calculations are listed in Table 7. For example, at 1.6 kHz, the calculation

TABLE 7

DATA USED IN DERIVING THE FREQUENCY RESPONSE 1 mm
FROM THE TYMPANIC MEMBRANE

Frequency kHz	E_E	20 log 0.66/E_E	L_E	K*	L_T
0.8	.00368	45.1	110.1	+0.0	110.3
1.2	.00256	48.2	113.2	-0.5	112.7
1.6	.00356	45.4	110.4	-2.5	107.9
2.0	.00599	40.8	105.8	-2.5	103.3
2.4	.00955	36.8	101.8	-2.5	99.3
2.8	.00866	37.6	102.6	-0.5	102.1
3.2	.00553	41.5	106.5	+1.0	107.5
3.6	.00539	41.8	106.8	-2.0	104.8
4.0	.00860	37.7	102.7	-2.0	100.7
4.4	.01718	31.7	96.7	+1.0	97.7
4.8	.03052	26.7	91.7	+2.0	93.7
5.2	.06299	20.4	85.4	+6.5	91.9
5.6	.06184	20.6	85.6	+2.5	88.1
6.0	.06192	20.6	85.6	+1.5	87.1
6.4	.09317	17.0	82.0	+2.5	84.5

*rounded to the nearest 0.5 dB

was as follows:

$$L_{EM} = 65 \text{ dB SPL} + 20 \log_{10} 0.66v/0.00356v$$

$$L_{EM} = 65 \text{ dB SPL} + 45.4 \text{ dB}$$

$$L_{EM} = 110.4 \text{ dB SPL}$$

For the sound pressure levels developed at a position 1 mm from the tympanic membrane, by 0.66 volts, the values of K, plotted previously in the lower portion of Figure 19, were added to L_{EM} at each frequency. At 1.6 kHz, for example, the sound pressure level 1 mm from the tympanic membrane that would have been produced by 0.66 volts was calculated as follows:

$$L_T = L_{EM} + K$$

$$L_T = 110.4 \text{ dB SPL} + -2.5 \text{ dB}$$

$$L_T = 107.9 \text{ dB SPL}$$

where L_T is the derived sound pressure level produced by 0.66 volts and which was measured 1 mm from the tympanic membrane, and K is the value (at each frequency) which represented the difference between the level at the earmold tip and the level at the tympanic membrane. The values of K and L_T are listed in Table 7.

Probe-Tube Measurements at the 0-mm and the 5-mm Positions in the Ear Canal and These Measurements Compared With the Derived Data

In addition to the derived data, probe tube measurements were made at the 0-mm and the 5-mm probe-tube positions in ear canals. In these instances, a constant 0.016 volts appeared across the receiver's terminals. In order to make comparisons with the coupler data and the derived data, the mean data in these measurements were transformed by the formula: difference in dB = 20 $\log_{10}$ 0.66 volts/0.016 volts. Thus, 32.31 dB was added to the mean at each frequency in order to obtain the level which would have been developed with 0.66 volts applied to the hearing aid receiver. Table 8 lists the transformed means together with the standard deviations for these measurements.

The standard deviations associated with these measurements appear to be about the same size for the 0-mm and the 5-mm positions across frequencies. In addition the data at the 0-mm and 5-mm positions exhibit variability quite similar to two other investigations. Zachman (59) reported intersubject standard deviations of up to 6.7 dB for physical measurements in a measurement situation and frequency range comparable to those of this study. Similarly, Sachs and Burkhard (50) observed standard deviations of up to 5.0 dB at 7.0 kHz for measurements at a 5-mm position. In contrast, McDonald (35) reported standard deviations for similar measurements which were never greater than 3.5 dB in the frequency range below 4.0 kHz.

Figure 20 represents a comparison of the sound pressure levels measured at the 0-mm position measured with 0.016 volts input with the derived measurements made during the loudness balance experiment. (All levels were subsequently referred to a 0.66 volt input to the receiver.) The similarity of the two curves attests to the reliability with which the measurements in the ear canal were carried out.

Figure 21 illustrates the frequency response of the receiver-earmold system measured at a position 1 mm from the tympanic membrane listed previously in Table 7 and the frequency response curves measured at the 0-mm and the 5-mm positions in ear canals (reported previously in Table 8).

TABLE 8

MEAN SOUND PRESSURE LEVELS* AND STANDARD DEVIATIONS (in dB) FOR EAR CANAL MEASUREMENTS AT THE 0 mm AND AT THE 5 mm POSITIONS (N=8)

	0 mm Position		5 mm Position	
kHz	Mean	S.D.	Mean	S.D.
0.8	113.7	2.07	113.6	2.65
1.2	114.4	3.45	114.4	3.93
1.6	109.0	2.92	110.1	4.58
2.0	105.3	2.26	106.6	4.58
2.4	102.4	3.88	104.8	5.00
2.8	101.9	5.44	105.6	5.60
3.2	108.1	7.43	108.0	6.18
3.6	103.6	6.26	106.0	6.56
4.0	100.8	5.47	103.8	6.67
4.4	100.4	5.28	104.3	7.39
4.8	93.3	4.78	97.9	7.63
5.2	87.2	4.75	89.3	7.64
5.6	86.5	6.36	86.0	7.00
6.0	85.0	7.76	83.5	6.36
6.4	86.8	7.26	83.2	6.60

*These means represent the mean actually observed plus 32.31 dB as described on page 85.

Figure 20. Sound pressure levels measured at the 0-mm position in the ear canals and sound pressure levels at the earmold tip measured during the loudness balance procedure. The open circles represent the 0-mm data and the closed circles represent the derived data. (All levels are referred to 0.66 volts across the receiver's terminals.)

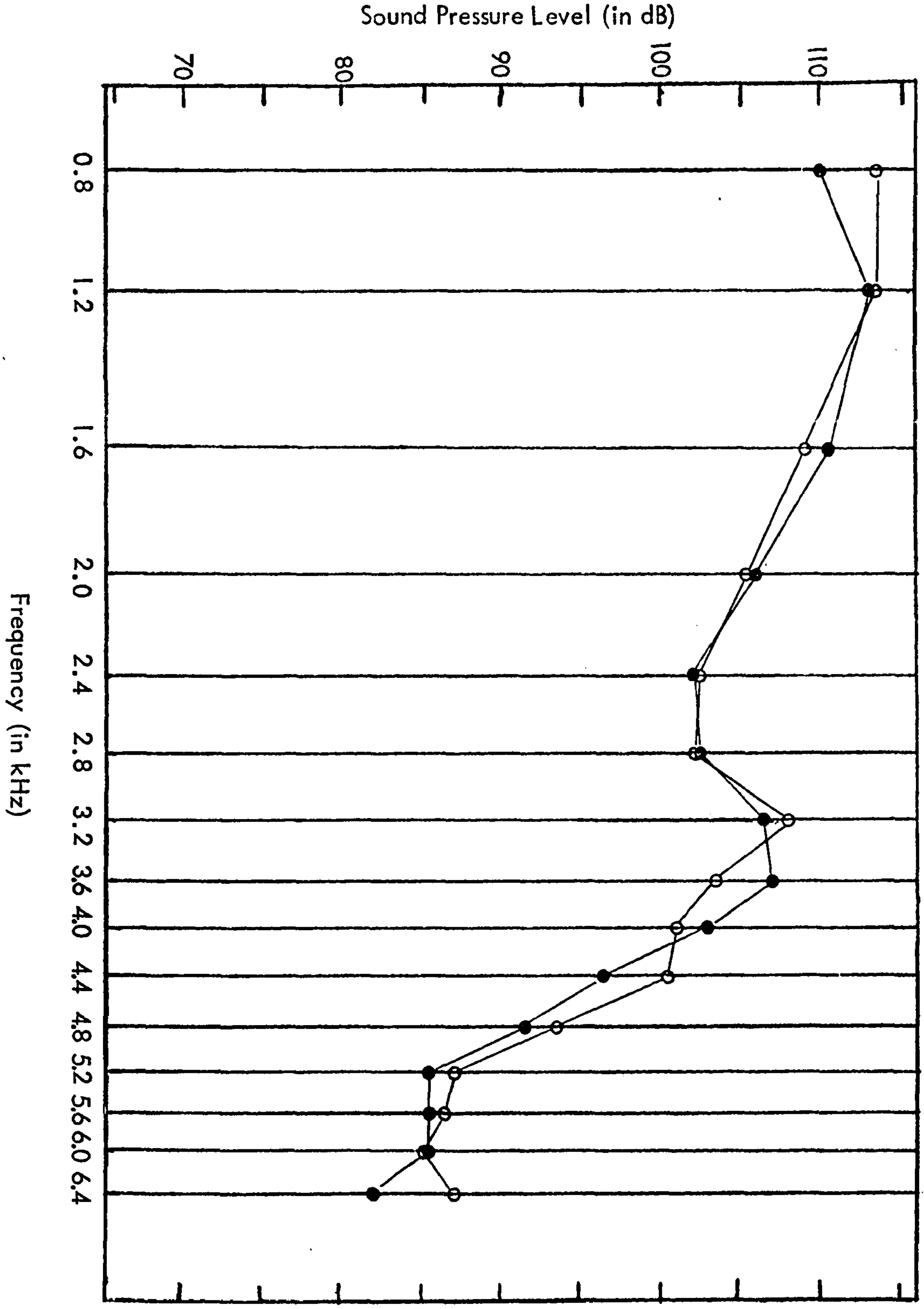
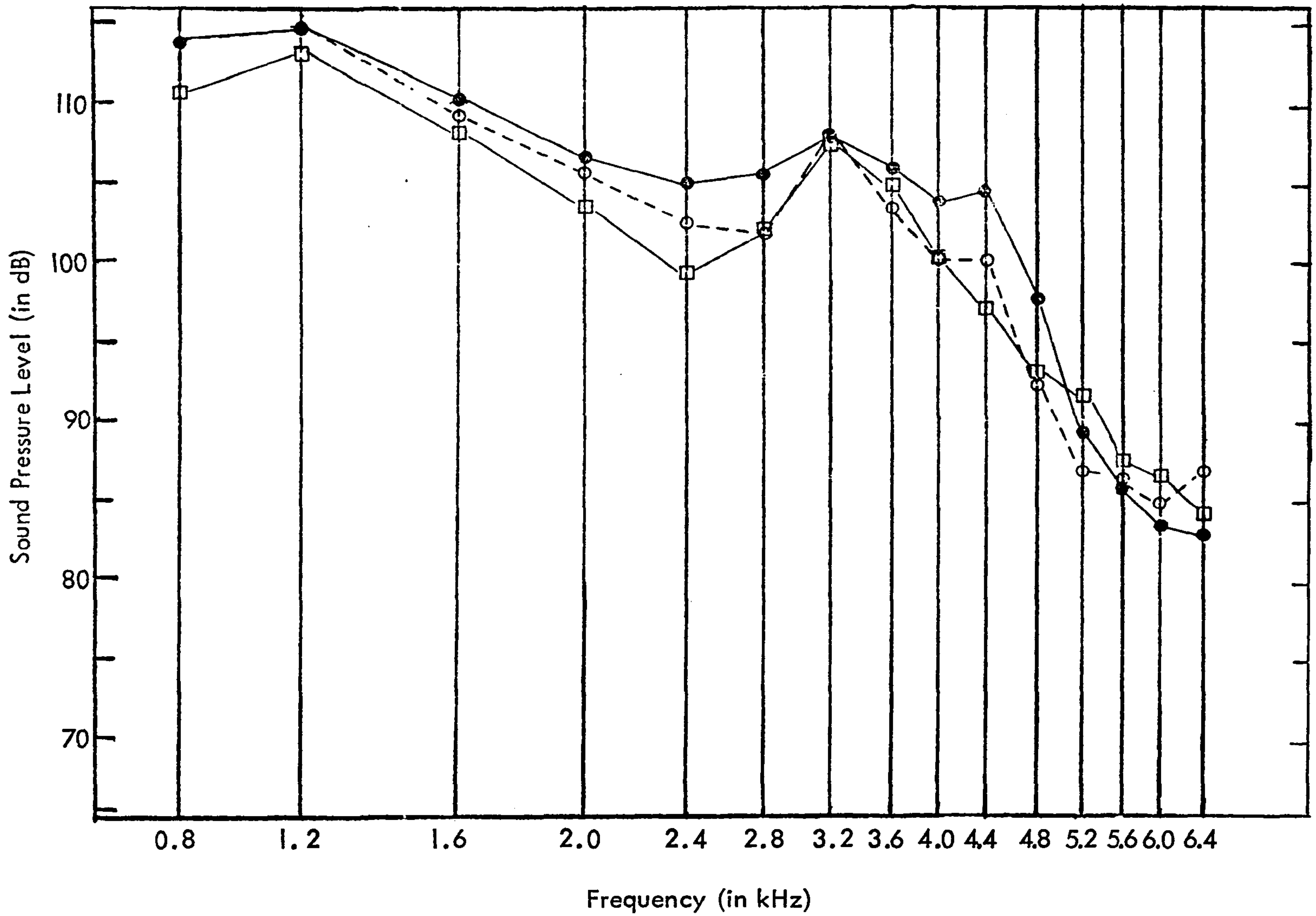

Sound Pressure Level (in dB)
70
80
90
100
110
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 21. Median sound pressure levels 1 mm from the tympanic membrane derived from the loudness balance procedure, sound pressure levels measured at the 5-mm position in ear canals, and sound pressure levels measured at the 0-mm position in ear canals. The closed circles represent the 5-mm data, the open circles represent the 0-mm data, and the open squares represent the data representing measurements 1 mm from the tympanic membrane.


Sound Pressure Level (in dB)
110
100
90
80
70
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

The 0-mm curve essentially parallels the 5-mm curve up to 2.4 kHz where it falls below the latter by 2.0 dB. At 3.2 kHz, a resonance appears and, at that frequency, the 0-mm curve rejoins the 5-mm curve. After the resonant peak, the 0-mm curve falls 3.0 to 4.5 dB below its 5-mm counterpart. The curves cross between 5.2 and 5.6 kHz; above this frequency, the 5-mm curve lies below the 0-mm curve.

The curve representing the sound pressure level 1 mm away from the tympanic membrane falls below the other two curves at all frequencies below 2.8 kHz and lies below the 5-mm curve at 2.8 kHz. Through this range, for example, it courses 2.0 to 5.0 dB below the 5-mm curve. From 3.2 kHz, where the curves join, to 4.8 kHz the 1-mm curve falls below the 5 mm curve, reaching the greatest difference at 4.4 kHz (6.0 dB). From 5.2 to 6.0 kHz the 1-mm curve lies above the 0-mm and 5-mm curves while at 6.4 kHz it lies between them.

The orderly effects of probe-tube location upon SPL seen previously in the data gathered in the couplers, particularly in the 2-cc cavity, were not seen in the ear canal measurements. As discussed earlier, there is reason to believe that reactance varies with positions in a cavity. Particularly in the 2-cc cavity measurements of this investigation, the 0-mm measurements were substantially influenced by the probe tube's proximity to the sound inlet tube's orifice. A comparison of the 0-mm position ear canal data with the 5-mm ear canal data and with the tympanic membrane data shows that this effect does not occur in ear canal measurements. In this regard, the Zwislocki coupler produced results which are more like the data obtained in the ear canals than did the 2-cc cavity.

It is seen in Figure 21 (page 90) that the levels measured at the 5-mm position are substantially greater than the levels measured 1 mm from the tympanic membrane or at the 0-mm position. Hence, these data do not support Sachs' and Burkhard's recommendation, which was based only on coupler observations, that probe-tube measurements in ear canals be made at a 5-mm position in order to avoid adverse effects associated with positions near the sound-inlet tube's orifice. These effects apparently do not occur in the ear canal.

It is also seen in Figure 21 that at least for ear canals closed by an earmold there are only slight differences between measurements made at a mid-ear canal position and measurements made at a position near the tympanic membrane. No results have been reported in the literature with which these data may be compared; however, Zwislocki made SPL measurements at two positions in the open ear canal when the subject's head was placed in a sound-field. (Instead of measurements made at the earmold tip, measurements were made 0.9 cm from the entrance to the ear canal, which, according to Zwislocki, corresponds to the tip of insert devices such as earmolds.) He found that for frequencies below 2.5 kHz sound pressure levels measured at the tympanic membrane were no different from those measured at the mid-ear canal position. Above that frequency the level at the tympanic membrane gradually increased relative to the mid-ear canal position reaching a difference of 8.0 dB at 6.0 kHz (approximately the uppermost frequency of interest in this study). Figure 21 does not reveal such a trend for the closed ear canal data reported here.

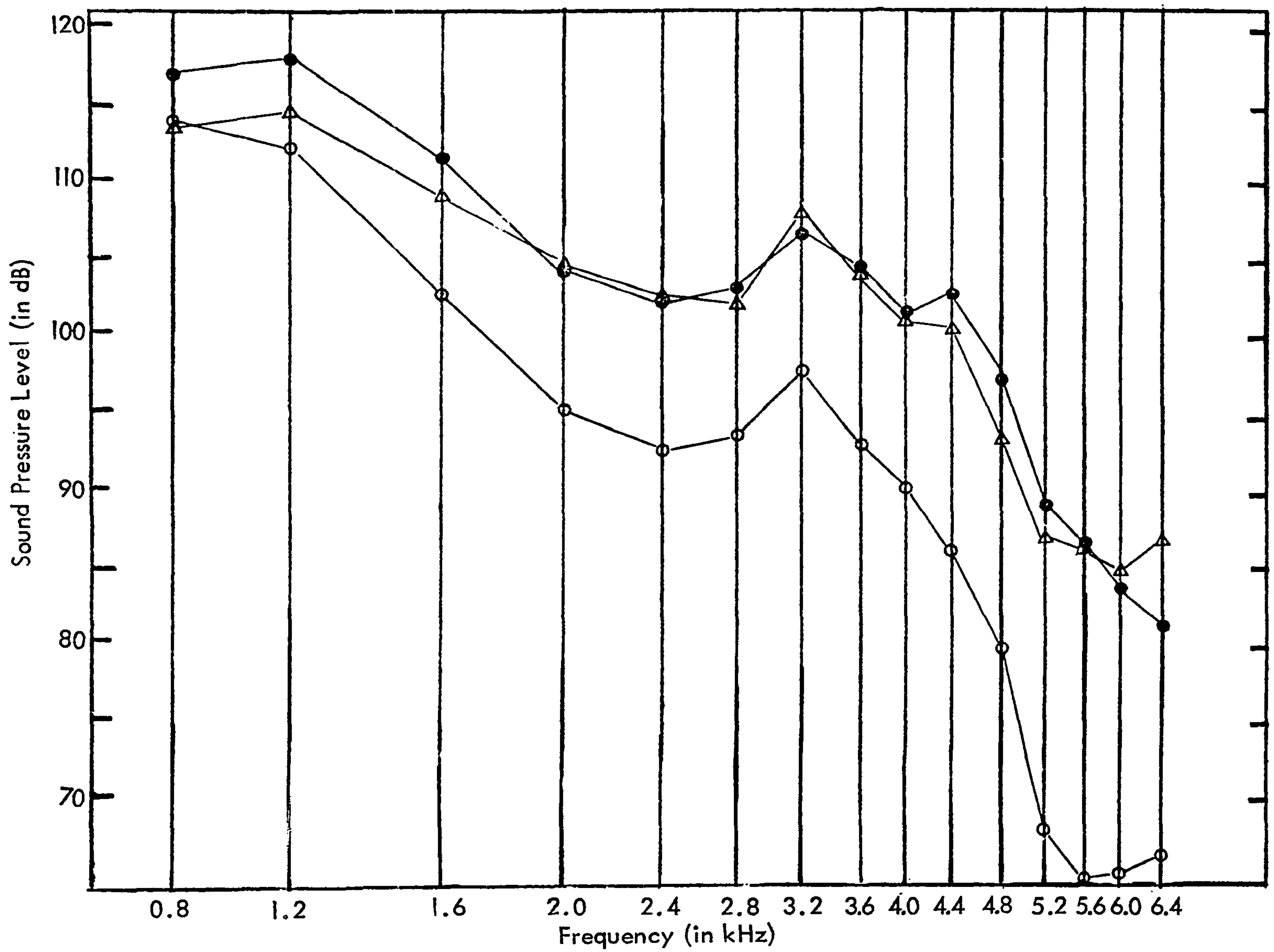
Sound Pressure Levels Developed in Ear Canals Compared with Sound Pressure Levels Developed in the Couplers

Figures 22, 23 and 24 allow a comparison among the sound pressure levels, by frequency, developed in the Zwislocki coupler, the 2-cc cavity, and the human ear canals at each probe-tube position. The coupler data obtained at the 0- and 5-mm positions (the numerical values appear in Appendix II) have been corrected for the probe-tube's frequency response. The coupler microphone numberical data are listed in Appendix I. Data for the 0- and 5-mm positions in the ear canals have previously appeared in Table 8 (page 86) while the data representing measurements 1 mm from the tympanic membrane have been listed in Table 7 (page 83).

Figure 22 shows the extraordinary similarity between the sound pressure levels developed in the Zwislocki coupler and the ear canals when the measurements are made in the 0-mm position. Differences between the two sets of data appear primarily in the frequency region below 1.6 kHz. From 1.6 to 4.0 kHz, the two curves essentially intertwine. At 4.4 kHz and through 5.6 kHz, the levels in the Zwislocki coupler range from 0 to 4 dB greater. At 6.4 kHz, the level in the Zwislocki coupler falls below that in the ear canals by 5 dB. The levels measured at the 0-mm position in the 2-cc cavity fall below the other two curves beginning at 1.2 kHz. The differences are relatively constant until 4.0 kHz where the difference increases to approximately 23 dB at 5.6 kHz.

Figure 23 is a graph of the same nature, except that the data represent levels observed at the 5-mm position. As in the previous figure, there is a striking similarity between the ear canal data and the data

Figure 22. Sound pressure levels observed at the 0-mm position in ear canals (triangles), in the Zwislocki coupler (closed circles,) and in the 2-cc cavity (open circles).



Sound Pressure Level (in dB)
120
110
100
90
80
70
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 23. Sound pressure levels observed at the 5-mm position in ear canals (triangles), in the Zwislocki coupler (closed circles), and in the 2-cc cavity (open circles).

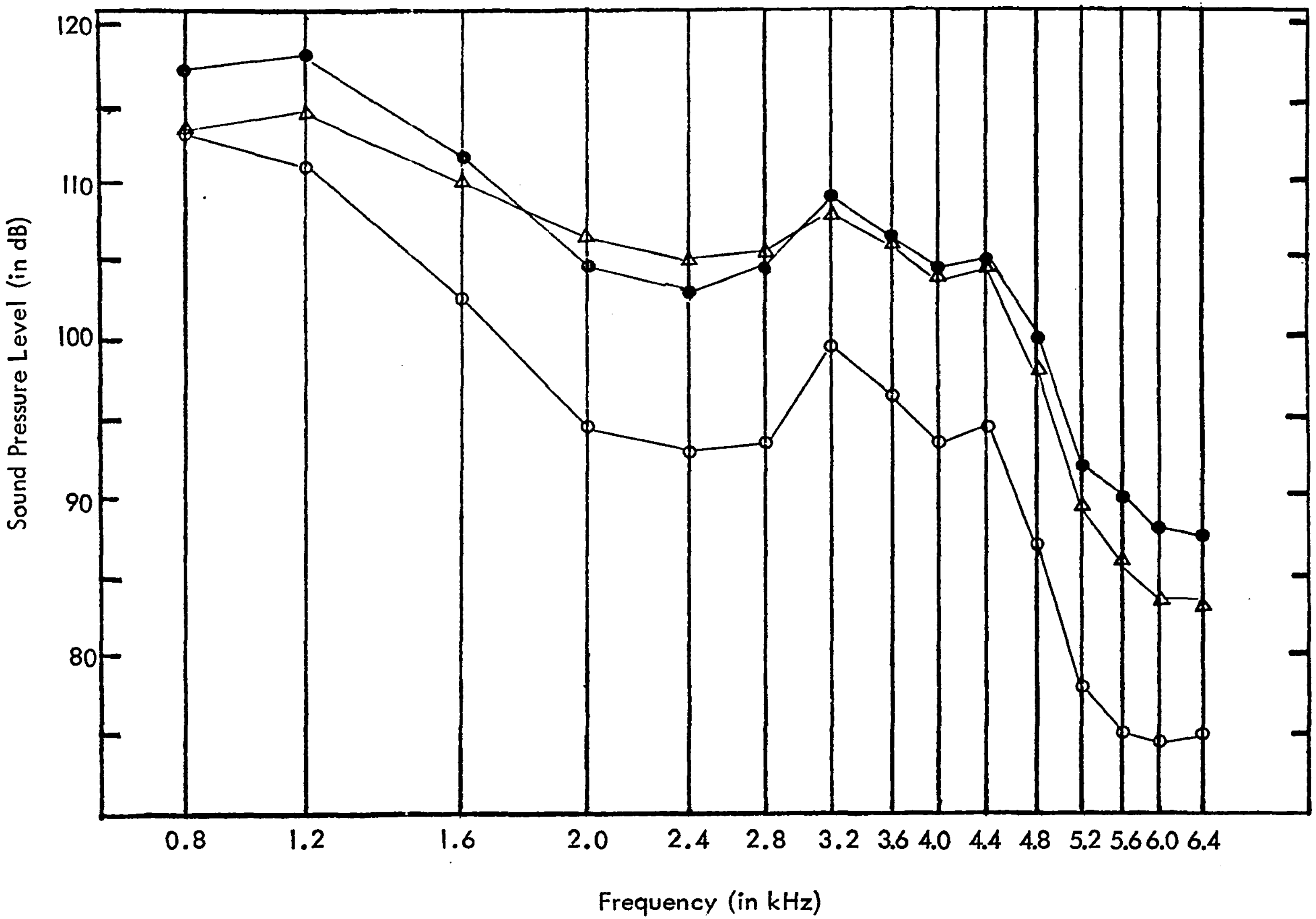
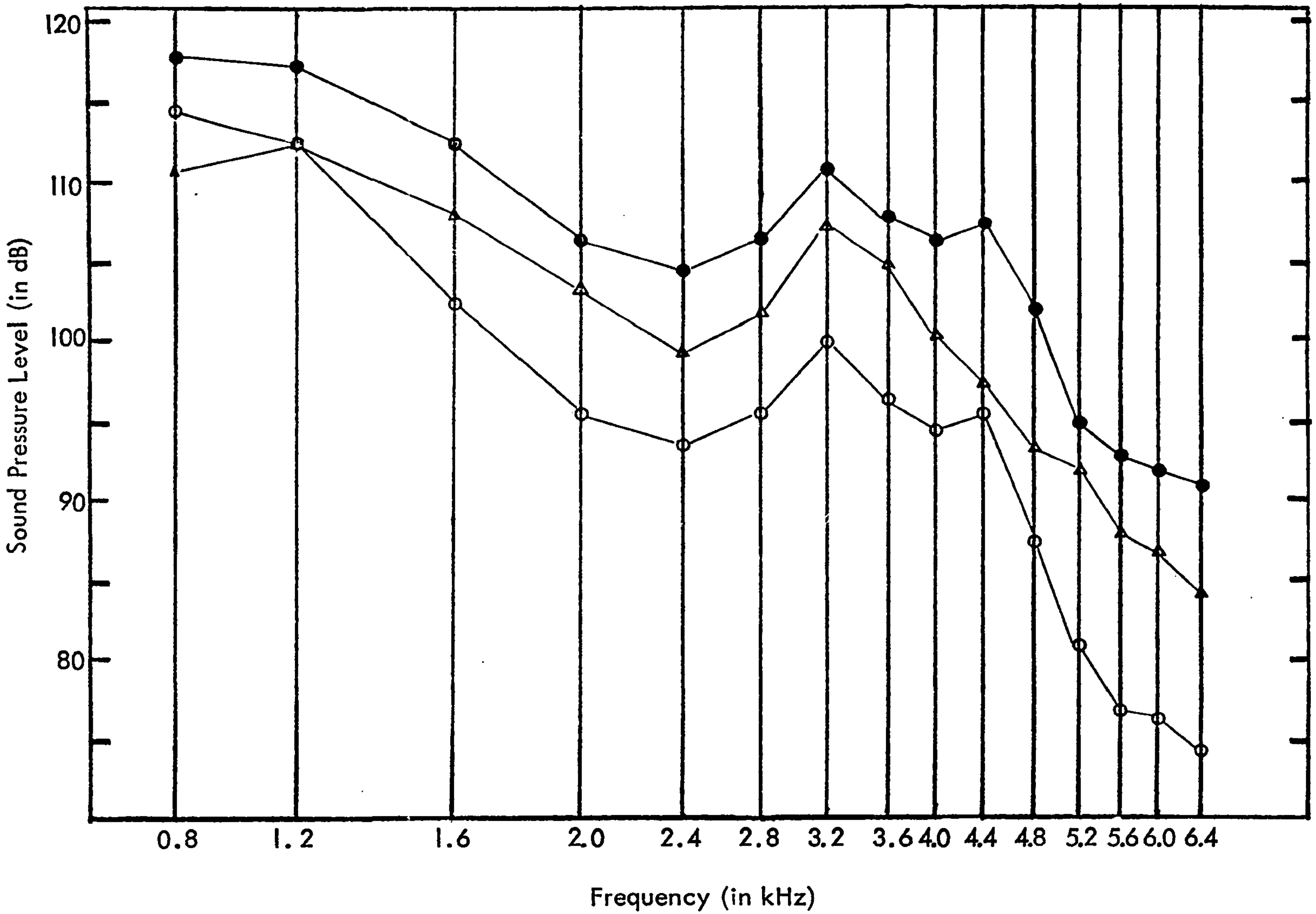

Sound Pressure Level (in dB)
120
110
100
90
80
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

Figure 24. Derived sound pressure levels 1 mm away from the tympanic membrane (triangles), and sound pressure levels observed 1 mm from the coupler bottom in the Zwislocki coupler (closed circles) and in the 2-cc cavity (open circles).


120
110
100
90
80
Sound Pressure Level (in dB)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4
Frequency (in kHz)

for the Zwislocki coupler. Above 4.0 kHz, the levels in the ear canal fall below the Zwislocki coupler data by 4 to 5 dB through 6.0 kHz. At the lower frequencies, levels measured at the 5-mm position are very similar to the levels measured at the 0-mm position in the same measurement environment (see Figure 10, page 51). Therefore, the differences among the three curves in Figures 22 and 23 are approximately the same in this frequency region. In the higher frequencies, the levels observed at the 0-mm position in the 2-cc cavity diverge from those measured at the 5-mm position (see Figure 10). Therefore, the relationship of the three curves in Figures 22 and 23 is not maintained. This observation is probably attributable to the effects noted earlier associated with locating the probe tube near the sound-inlet tube in a hard-walled cavity.

Figure 24 shows the derived frequency response 1 mm from the tympanic membrane (column 6 from Table 7) and the frequency responses as recorded from the coupler microphones of the 2-cc cavity and the Zwislocki coupler. The SPL developed at the position near the tympanic membrane are clearly less than those developed in the Zwislocki coupler. (Appendix V lists the differences between sound pressure levels observed near the tympanic membrane and those observed at the analogous positions in the Zwislocki coupler.) This result would not have been anticipated on the basis of the relationships revealed by the measurements at 0-mm and 5-mm (Figures 22 and 23) although as expected, the data for the position near the tympanic membrane are clearly greater than those developed near the 2-cc cavity bottom. Recall that the curve for the measurements made 1 mm from the tympanic membrane was derived from the alternate binaural loudness balance results which were in turn based on a wholly different set of physical measurements. It is unclear at this time whether the data plotted in Figure 24 reveal that the method used was not sufficiently accurate or valid in some regard or whether the differences revealed in Figure 24 are real, produced by some as yet unrecognized effect. Further investigation on this point will be required.

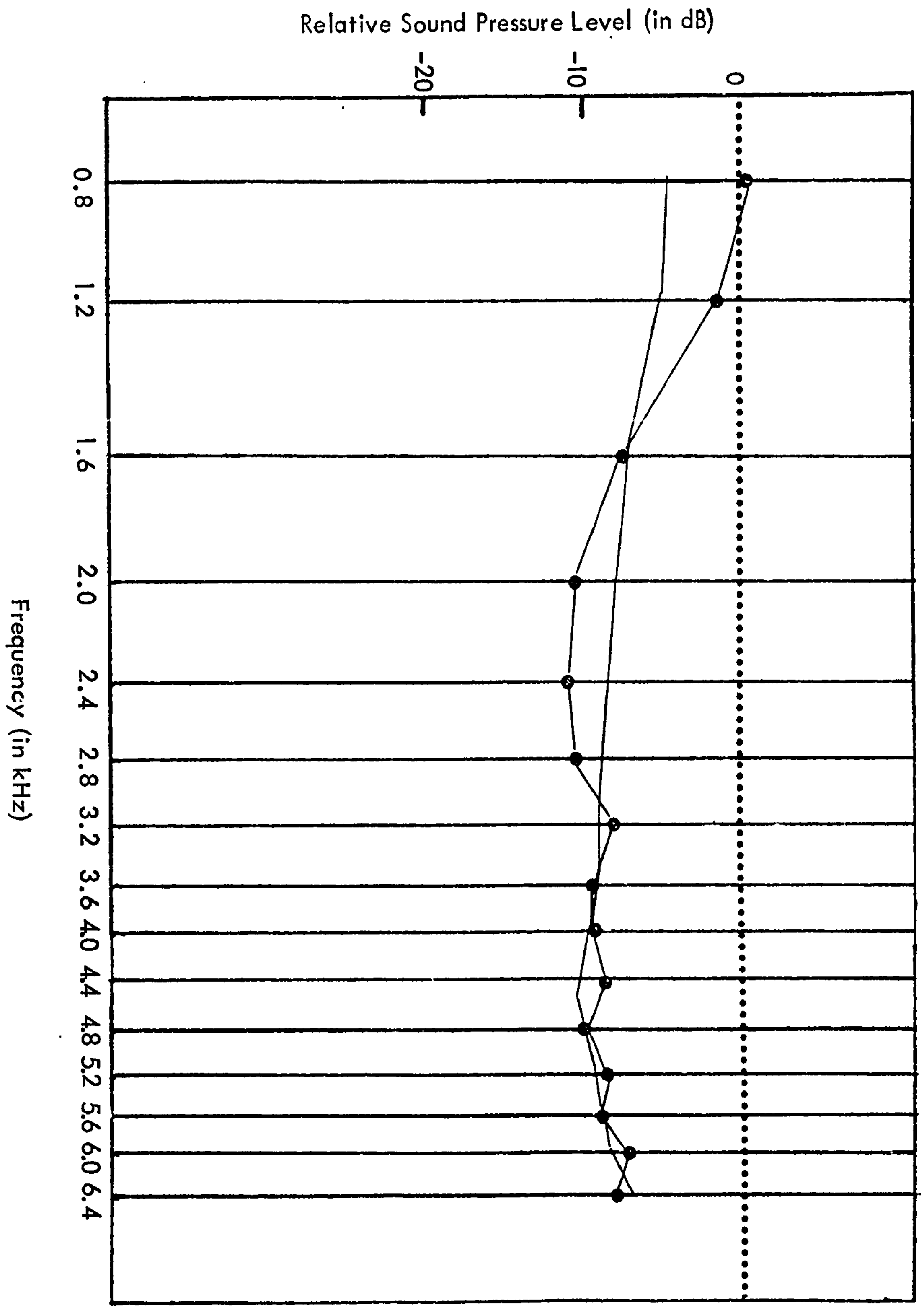
Previous discussion in this chapter pointed out that Zwislocki (60,61) observed the same differences between a mid-position and the tympanic membrane in the open ear canal as he did in the analogous locations in the open Zwislocki coupler. The differences for the current study, based on the same measurement locations, in the Zwislocki coupler (closed by an earmold) agreed very well with Zwislocki's data. In ear canals (closed by an earmold), however, comparable differences between the two measurement locations were not observed in the current study. In order to reconcile further study of SPL at different measurement locations in open and closed ear canals will be necessary. Such research may be particularly informative in view of Zwislocki's observation that an electrical analog of the ear canal based on acoustic impedance measurements in closed ear canals does not simulate the actual SPL difference between mid-canal and tympanic membrane locations in an open ear canal (60).

Of the several reports citing acoustic performance differences between the 2-cc coupler and human ear canals, the studies of McDonald (34), Zachman (59), and Sachs and Burkhard (50) were conducted in a manner which allows comparison with the results reported for the present investigation. In both studies, the probe-tube's tip was placed flush with the sound inlet tube (analogous to the 0-mm position in this study). McDonald's data (his Figure 11, p.74) for the difference between the sound level recorded at the coupler microphone and that recorded at 0-mm position in the ear canal are not more than 1.5 dB different from the values observed in this study in the frequency range from 1.0 through 4.0 kHz (4.0 kHz was the uppermost frequency studied by McDonald). The ear canal versus 2-cc coupler data for this study are in good agreement with data, derived in the same manner, reported by Zachman.

Differences between acoustic measurements made in ear canals and in the 2-cc coupler were also reported by Sachs and Burkhard (50). They made probe tube measurements in ear canals with the probe-tube tip extended 5-mm beyond the sound-inlet tube's orifice. The measurements made in the ear canal were compared to levels recorded from the coupler microphone. Figure 25 shows this result (from their Figure 2) together with the analogous result observed in the present investigation. Except for the frequencies below 2.8 kHz where differences of from 2.0 to 4.0 dB are seen, very good agreement between the results of the two investigations is apparent.

Only one investigation (Sachs and Burkhard) has compared sound pressure levels developed in ear canals with sound pressure levels developed in the Zwislocki coupler when the sound pressures were developed by a hearing-aid receiver-earmold combination. Among other things, Sachs and Burkhard measured sound pressure levels with the coupler microphone and observed the sound pressure levels 5-mm beyond the earmold tip in ear canals. The current study is in good agreement with the latter

Figure 25. Sound pressure levels observed from the 2-cc coupler microphone plotted relative to the level observed at the 5-mm position in ear canals for this investigation and for the investigation of Sachs and Burkhard (50). The solid line represents the data reported by Sachs and Burkhard and the closed circles represent the data for this investigation.


Relative Sound Pressure Level (in dB)
-20
-10
0
Frequency (in kHz)
0.8
1.2
1.6
2.0
2.4
2.8
3.2
3.6
4.0
4.4
4.8
5.2
5.6
6.0
6.4

study in this regard as no differences in excess of 2.0 dB are apparent through the frequency range from 1.6 to 6.4 kHz. At 0.8 and 1.2 kHz the levels obtained in the present investigation are 3.0 to 4.0 dB greater than those obtained by Sachs and Burkhard.

A review of the literature also shows that, to this date, the present investigation is the sole attempt to compare couplers and ear canals on the basis of sound pressure levels (developed by a hearing-aid receiver-earmold combination) at the tympanic membrane and at the analogous position in couplers. There are, therefore, no studies which are directly comparable on this point. In addition, there are no studies with which to compare the differences between the levels at or near the tympanic membrane and levels elsewhere in the ear canal with the ear canal occluded by an earmold.

CHAPTER V

SUMMARY AND CONCLUSIONS

Acoustic couplers have been used for at least thirty years to evaluate the performance characteristics of hearing aids. The most commonly used device has a simple cylindrical shape and a volume of 2 cc. This cavity, along with several sound-input tube configurations, has been specified for use in hearing-aid receiver measurements by the American National Standards Institute (2). Recently, a more sophisticated device has been suggested for use in assessing the acoustic performance of hearing aids. In 1970, Zwislocki developed a coupler which also is basically a cylindrical device, but, which in addition contains acoustic networks intended to replicate the acoustic impedance of the human ear (60).

The 2-cc coupler, almost from the time of its development, was suspected of inadequately simulating the acoustic load of the human ear. Estimates of the differences between sound pressure levels developed in the 2-cc coupler and in human ear canals varied, but most estimates agreed that discrepencies were greatest in the frequency range above 1.0 kHz (16,25,34,50,54,58,59). The differences were variously attributed to diffraction of sound about the head (46), the resonance characteristics of the ear canal (46), differences in acoustic impedances between the coupler and ear canals (45), and leaks around the earmold when placed in the ear canal (45,50).

More recently Sachs and Burkhard (49) showed that the proximity of the orifices of the probe tube and the sound-inlet tube in a 2-cc cavity created an adverse acoustic measurement situation. Expanding upon a theory developed by Ingard (21), they asserted that inertance spreading around the sound inlet tube interacted with the stiffness of the air in the 2-cc cavity and created a sharp drop in sound pressure at a particular frequency. The frequency of the drop was dependent upon the location of the probe-tube tip. They suggested for ear canal measurements that the probe-tube tip be extended a distance of 5-mm beyond the earmold tip in order to avoid this artifact.

Zwislocki, after the development of his coupler, called for extensive measurements in order to provide definitive validation of the new device (60). Since that time, Sachs and Burkhard (50) reported that the sound pressure levels developed in human ear canals and in the Zwislocki coupler differed by no more than 3.0 dB in the frequency range from 0.8 kHz to 7.5 kHz. However, Sachs and Burkhard added Zwislocki's ear canal transformations (between a mid-canal location and the tympanic membrane) to their own ear canal data. They did not make measurements at the tympanic membrane.

The purpose of this investigation was to compare the acoustic performance of a hearing aid-receiver placed on a 2-cc cavity and placed on a Zwislocki coupler with the performance of that same receiver attached to an earmold seated in the human ear canal. This study was particularly concerned concerned with the frequency region above 1.0 kHz.

The acoustic output of the receiver attached to earmolds for frequencies in the range from 0.8 kHz to 6.4 kHz was observed at three locations in the ear canals of eight normal-hearing listeners. One set of measurements was made with the probe-tube tip terminated at the tip of the canal portion of the earmold. Another set of measurements was made with the probe-tube tip at a point 5 mm beyond the earmold tip. The third set of measurements involved alternate binaural loudness balance judgements together with probe-tube measurements of the sound pressure level at a position 1 mm from the opposite tympanic membrane. This technique was utilized as a means of deriving the sound pressure level at the eardrum of an ear occluded by an earmold.

The sound-pressure levels recorded at each of the probe-tube positions in the ear canals were compared with those developed by the same receiver-earmold combination at the three analogous positions in a 2-cc cavity and in a Zwislocki coupler. That is, probe-tube measurements were made flush with the earmold tip, 5 mm beyond the earmold tip, and 1 mm from the coupler bottom.

Results

Probe-Tube Location in Ear Canals, in the 2-cc Coupler, and in the Zwislocki Coupler

Good agreement was seen among the observed results as a function of probe-tube position in the 2-cc cavity and the Zwislocki coupler used in this investigation and the theoretical result provided by Sachs (47). In addition the measurement position data of the current study for the Zwislocki coupler are in good agreement with the data reported by Zwislocki (60). Furthermore, the data which describes 2-cc cavity and Zwislocki coupler differences at various measurement positions are also in good agreement with the data reported by Sachs and Burkhard (50).

For the 2-cc cavity, there were no substantial differences among the sound pressure levels measured at the three probe-tube positions from 0.8 kHz to 2.8 kHz. For frequencies above 2.8 kHz, however, SPL at both the 5-mm and the 0-mm positions decreased as frequency was increased relative to the levels measured 1 mm away from the coupler bottom. Sound pressure levels observed at the 0-mm position were much less than those observed at the coupler bottom. At 6.0 kHz, for example, the probe-tube measurement at the 0-mm position was 22.5 dB less than the probe-tube measurement 1 mm from the coupler bottom.

For the Zwislocki coupler, there were again no substantial differences among the sound pressure levels observed at the three probe-tube positions in the frequency range from 0.8 to 2.8 kHz. Above 2.8 kHz, sound pressure levels at the 5-mm position decreased very slightly with increased frequency relative to the sound pressure levels observed 1 mm from the coupler bottom. The maximum difference was approximately 2.5 dB, occurring at 5.6 and 6.0 kHz.

The orderly differences as a function of probe-tube location which were seen in the coupler data, were not seen for ear-canal measurements. The sound pressure levels measured at the three positions in the ear canals were observed to be most similar for frequencies below 2.0 kHz; however, the levels for the 5-mm position were 2.0 to 4.0 dB greater than those for the tympanic membrane position. From 2.0 through 4.8 kHz, the levels for the 5-mm position were markedly greater than for the tympanic membrane position, and in this same frequency range, the 0-mm data were very similar to the tympanic membrane data. Above 4.8 kHz, the levels measured at the three positions did not differ to a remarkable extent.

The 2-cc cavity data of the present study support Sachs' and Burkhard's extension of Ingard's theory regarding the distribution of sound pressure in cylindrical cavities. It was noted that marked probe tube position effects in the 2-cc cavity occur because the 2-cc cavity is purely a reactive device. Therefore, inertance associated with the sound inlet tube interacts with the stiffness of the cavity and, at some frequency, sound pressure decreases. On the other hand, the acoustic load offered by the Zwislocki coupler and by ear canals is both reactive resistive. Therefore, when the inertance and the stiffness cancel, pressure does not decrease as much because of sound pressure developed across the resistive component. The Zwislocki coupler data are far less supportive of Sachs' and Burkhard's theory and the data collected in ear canals lead to the conclusion that the theory does not explain sound pressure measurements in ear canals, at least not over the frequency range of interest in this study.

The data obtained in this investigation neither refute nor support Sachs' and Burkhard's suggestion that probe-tube measurements in ear canals, through earmolds, be made at a position 5-mm beyond the earmold tip. While the matter merits further investigation, the present data indicate that essentially the same result is obtained whether the probe tube is placed at a 0-mm position in ear canals or at a position very near the tympanic membrane.

Sound Pressure Levels Developed in the Couplers and in the Ear Canals

The data show that different results are obtained for comparisons between ear canals and couplers when the probe tube is placed at analogous positions in the two environments. For example, when the sound pressure levels observed in the 0-mm position in the 2-cc cavity were compared to those levels observed at the 0-mm position in ear canals, the acoustic level in the 2-cc cavity was substantially lower than in the ear canals, particularly in the frequency region above 2.8 kHz. This underestimation of the actual level by the 2-cc cavity results from sound source and probe-tube proximity effects. In addition, when the sound pressure levels observed in the 5-mm position in the 2-cc cavity were compared to the sound pressure levels observed at the 5-mm position in ear canals, the 2-cc cavity again provided an underestimation of the level in the ear canals, although to a lesser extent. This underestimation may also be attributable, in part, to the proximity of the probe tube to the sound-inlet tube.

When sound pressure levels developed in the Zwislocki coupler and the sound pressure levels developed in ear canals are compared on the basis of 0-mm measurements, excellent agreement is found. There is less similarity between the Zwislocki coupler and ear canal frequency response based on the 5-mm measurements, but good agreement between the two is still maintained. When the sound pressure levels developed in ear canals are measured from the coupler microphone (or at a probe tube position 1 mm away from the coupler microphone when probe tube attenuation characteristics are corrected) and compared to the sound pressure levels recorded 1 mm from the tympanic membrane, the Zwislocki coupler appears to overestimate the sound pressure levels developed in closed human ear canals. It was speculated in Chapter IV that the reasons for these differences may, in part, be attributed, at least in a general way, to the differences between impedance measured in a closed cavity and impedance actually existent in an open ear canal.

In conclusion, the data collected in current investigation show that the sound pressure levels developed in the 2-cc cavity substantially underestimate the sound pressure levels developed at the three analogous positions in the ear canals of human subjects. Furthermore, sound pressure levels measured at the 0-mm and 5-mm positions in the Zwislocki coupler are highly predictive of measurements made at the analogous positions in human ear canals. However, levels measured from the microphone located at the bottom of the Zwislocki coupler appear to overestimate the levels measured 1 mm from the tympanic membrane of human subjects.

No other study has been reported in the literature which compared sound pressure levels developed in couplers to sound pressure levels generated by the same hearing-aid receiver-earmold system measured at a position near the tympanic membrane. It must be recalled that the frequency response of the hearing-aid receiver-earmold system representing measurements 1 mm from the tympanic membrane was derived on the basis of an alternate binaural loudness balance procedure. For some of the differences reported in this document, therefore, the data may reflect physical influences inherent in the method. Subsequently, partial replication of that portion of this investigation is suggested because further verification of the effects of probe-tube position (when the probe tube is placed through an earmold) in ear canals is requisite for further understanding and development of couplers which are intended to simulate the acoustic load presented by the human ear canal.

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APPENDIX I

MEAN SOUND PRESSURE LEVELS FOR THE 2-cc CAVITY AND THE ZWISLOCKI COUPLER ACROSS FREQUENCY AS MEASURED FROM THE COUPLER MICROPHONE

kHz	2-cc Cavity Mean	Zwislocki coupler Mean
0.8	114.3	117.9
1.2	112.7	118.6
1.6	102.6	112.3
2.0	95.7	106.6
2.4	93.6	104.3
2.8	95.3	106.5
3.2	99.8	111.1
3.6	96.4	108.2
4.0	94.3	106.4
4.4	95.6	107.3
4.8	87.7	101.8
5.2	80.8	95.2
5.6	77.0	92.8
6.0	76.6	92.2
6.4	74.6	91.0

APPENDIX II

MEAN SOUND PRESSURE LEVELS RECORDED FROM THE PROBE TUBE MICROPHONE AT THREE PROBE-TUBE POSITIONS IN THE 2-cc CAVITY AND IN THE ZWISLOCKI COUPLER (N=16 EARMOLDS)

kHz	2-cc Cavity			Zwislocki Coupler		
	1 mm bottom	5 mm	0 mm	1 mm bottom	5 mm	0 mm
0.8	110.91	109.69	110.44	114.06	113.69	113.69
1.2	103.69	102.22	102.85	109.50	109.00	108.91
1.6	89.53	88.84	88.75	98.97	98.16	97.77
2.0	82.16	80.65	80.88	91.84	90.66	89.94
2.4	80.69	79.28	78.97	90.46	89.53	88.63
2.8	86.66	84.56	84.28	96.50	95.66	94.13
3.2	92.97	91.97	89.84	102.13	101.72	99.16
3.6	81.31	80.75	77.53	92.44	90.94	89.03
4.0	74.84	73.63	69.84	85.84	84.28	81.66
4.4	73.47	71.88	66.72	84.19	82.66	79.94
4.8	64.31	63.06	55.53	77.19	75.97	72.81
5.2	58.25	56.09	45.44	72.18	70.00	67.16
5.6	57.19	54.25	43.06	71.44	69.00	65.25
6.0	60.41	57.25	47.85	74.00	71.22	66.44
6.4	53.63	52.94	44.09	67.91	65.34	59.03

APPENDIX III

PROBE-TUBE CORRECTION VALUES*, in dB,
BY FREQUENCY

kHz	Probe-Tube Correction Value
0.8	3.5
1.2	9.0
1.6	13.5
2.0	14.0
2.4	13.5
2.8	9.0
3.2	7.5
3.6	15.5
4.0	20.0
4.4	22.5
4.8	24.0
5.2	22.0
5.6	21.0
6.0	17.0
6.4	22.0

*Rounded to the nearest 0.5 dB. The value's derivation is discussed in the text, page 72.

APPENDIX IV

MEANS AND STANDARD DEVIATIONS OF THE COMPARISON SIGNAL LEVELS WHEN SET AT ADJUDGED EQUAL LOUDNESS TO A 65 dB SIGNAL IN THE OPPOSITE EAR*
(Corrected for Probe-Tube Response)

	Conditions A and C		Conditions B and D	
kHz	Mean	S.D.	Mean	S.D.
0.8	65.5	4.96	66.1	4.72
1.2	66.8	9.10	63.0	2.80
1.6	69.4	6.37	63.5	4.78
2.0	66.6	7.30	62.5	5.54
2.4	69.5	8.64	62.1	3.05
2.8	68.3	9.75	62.5	6.30
3.2	67.4	11.85	67.0	5.00
3.6	69.8	5.80	66.3	3.91
4.0	68.5	8.19	64.2	6.68
4.4	67.7	6.79	68.7	7.69
4.8	69.4	9.33	71.1	4.71
5.2	69.5	12.37	70.6	5.50
5.6	65.5	10.26	70.2	8.38
6.0	63.6	7.23	67.8	9.17
6.4	63.8	4.89	70.7	7.93

*When the reference was presented by the loudspeaker, the level was set at 65 dB SPL 1 mm from the eardrum at each frequency. Conversely, when the signal was presented by the receiver, the level was set at 65 dB SPL at the tip of the earmold at each frequency.

APPENDIX V

DIFFERENCES (in dB) BETWEEN SOUND PRESSURE LEVELS OBSERVED NEAR THE TYMPANIC MEMBRANE (N=16) AND THOSE OBSERVED AT THE ANALOGOUS POSITIONS IN THE 2-cc CAVITY AND IN THE ZWISLOCKI COUPLER

Frequency kHz	2-cc cavity vs. ear canal	Zwislocki coupler vs ear canal
0.8	+4.0	+7.5
1.2	0.0	+5.9
1.6	-5.3	+4.4
2.0	-5.8	+3.3
2.4	-5.7	+5.0
2.8	-6.8	+4.4
3.2	-7.7	+3.6
3.6	-8.4	+3.4
4.0	-6.4	+5.7
4.4	-2.1	+9.6
4.8	-6.0	+8.1
5.2	-11.1	+3.3
5.6	-11.1	+4.7
6.0	-10.5	+5.1
6.4	-9.9	+6.5